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Slash Fire Atmospheric Pollution

by

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The use of proprietary or brand names does not imply approval of the product to the exclusion of others which may also be suitable.

CONTENTS

List of Figures

List of Tables

1. INTRODUCTION

In the Pacific Northwest, as in many other parts of the country, burning is the standard method for disposal of undesirable waste including logging debris and agricultural residue. About 81,000 hectares (200,000 acres) of logging slash are burned annually west of the Cascade Range in the States of Washington and Oregon. In addition, 101,000 hectares (250,000 acres) of grasslands are burned in Oregon.[1] Many other forms of residue are also disposed of by burning.

Burning of waste contributes unknown quantities of gases and particulates to the atmosphere which may result in local or areawide pollution. In many cases, burning presently appears to be the most practical and economical way of slash disposal. It is hoped that in the future more complete utilization of logging residues will eliminate the necessity of burning. But until then, prescribed burning may be the only way to reduce fire hazard and thus the possibility of sustained pollution from wildfires occurring during periods of limited ventilation or low inversions.

Contribution of burning of agricultural wastes to air pollution has been studied in California by McElroy,[2] Bell and Waggoner (1961),[3] Feldstein et al. (1963), and Darley et al. (1966), but only limited information has been available on the part played by slash disposal. In addition to our project, current research on the subject is being conducted at Oregon State University and Washington State University in cooperation with the Northern Forest Fire Laboratory at Missoula, Montana. The objectives of these studies are similar, but the methods, fuels, and environmental conditions are quite different (Fritschen 1967). This parallel research is justifiable because of the complexity of the problem and because techniques found optimum for minimizing pollution in one geographical region may not be universal.

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[1] Metric units are used in this report; see 9.2 for conversion factors.

[2] McElroy, G. Agriculture and air pollution. 1959. (Unpublished report, Univ. Calif. Ext. Serv., Berkeley.)

[3] Names and dates in parentheses refer to References p. 39.

Feldstein et al. (1963) state the general rule of thumb that the higher the combustion temperature and the longer the residence time at that temperature, the more complete the combustion will usually be if there is enough oxygen present. They offer data from single- and multiple-chamber incinerators which support the rule of thumb. However, local pollution is a function of incomplete combustion, total amount of material consumed, and completeness of dispersion. Furthermore, the primary objective of slash burning is not complete consumption, but to (1) expose sufficient mineral soil for regeneration, (2) reduce fire hazard, and (3) reduce undesirable species. Since fire hazard — especially ignition potential, rate of spread, and initial buildup — is directly related to the amount and percentage of fine fuel present, the objectives of slash disposal and minimum pollution may be achieved by a hot fire of sufficient duration to consume the fine fuels under favorable conditions for atmospheric dispersion. The hot fire, under field conditions, will provide the additional buoyant lift needed for dispersion.

2. OBJECTIVES

The primary objective of this project was to investigate the current practice of slash burning in relation to air pollution. The hypothesis tested was that incomplete combustion and, consequently, greater emissions result from low-temperature fires. Low fire temperatures are usually associated with broadcast burns because of relatively low discontinuous available fuel loading and slow ignition techniques with a slow buildup of fire intensity. A "safe" fire is an implicit management objective. Conversely, piled slash, with higher available fuel loading and arranged so that oxygen was not limiting, could be expected to burn more completely and at higher temperatures, producing less pollution.

The results of the field tests were to be compared with laboratory burns, with respect to burning characteristics and gaseous and particulate emissions, to determine whether the salient features of a field test can be modeled.

3. EXPERIMENTAL METHODS

3.1. Experimental Sites

Most of the research experiments of this project were carried out at the Charles Lathrop Pack Experimental Forest of the University of Washington. This area is located at the southern boundary of Pierce County, Washington, 35 kilometers south of Puyallup, 45 kilometers southeast of Tacoma, 48 kilometers southeast of Olympia (fig. 1). The broadcast burn (3.1.1)[4] and the pile burn (3.1.2) were conducted on a portion of Pack Forest near the confluence of the Mashel and Nisqually Rivers, about 1 kilometer downstream (north) from the mouth of a 152-meter-deep canyon (fig. 2). The area selected for the burn is on an alluvial terrace at an elevation of 229 meters, 76 meters above the river. The land slopes gently to the northwest. To the south and east are deeply dissected foothills of Mount Rainier. To the north and west, the topography is more gently dissected outwash and ground moraine, deposited during the Vashon ice age. Vegetation in the area regenerated naturally after a forest fire in the 1920's and consists of Douglas-fir with bracken fern, salal, trailing blackberry, hopclover, geranium, and other herbs and short shrubs.

3.1.1. BROADCAST BURN

Twelve hectares of Douglas-fir and associated species were clearcut during the spring and summer of 1967. The south 7.45 hectares of the 12.1-hectare area were burned in a broadcast burn on June 25, 1968. The area was center-fired with an electrical ignition system (see 3.3.1).

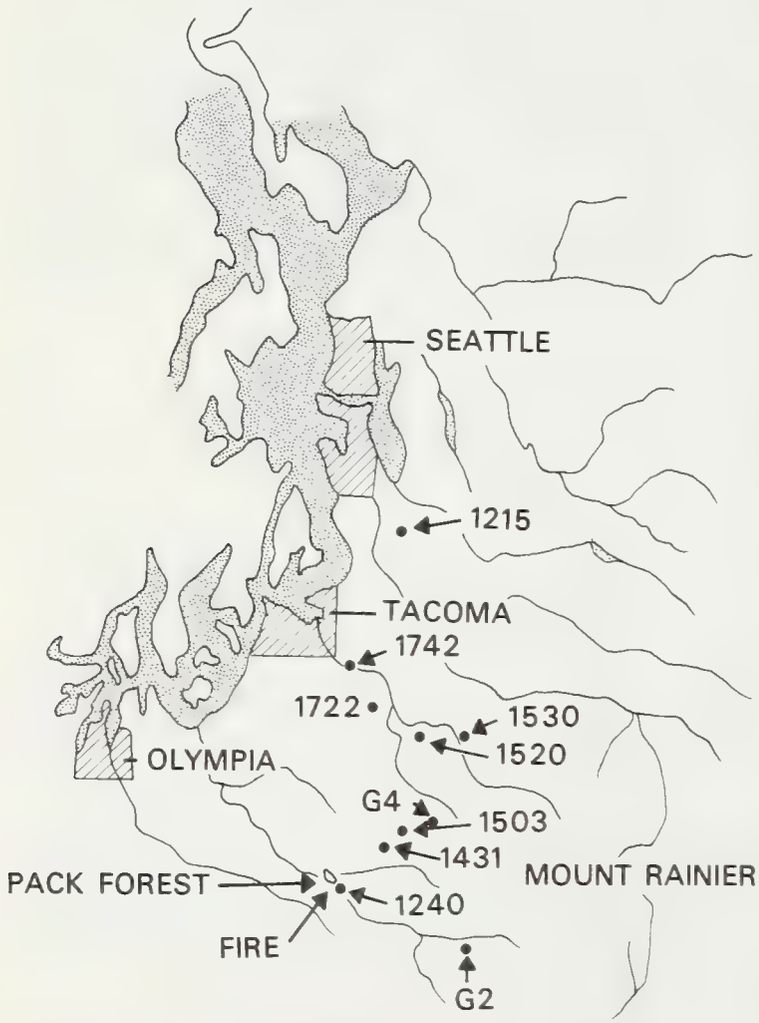


Figure 1. — Pack Forest and neighboring urban centers. Times (i.e., 1215) indicate location of aerial soundings and G2 and G4 indicate gas sample locations, discussed in chapter 3.

[4] Chapter 3, section 1, subsection 1.

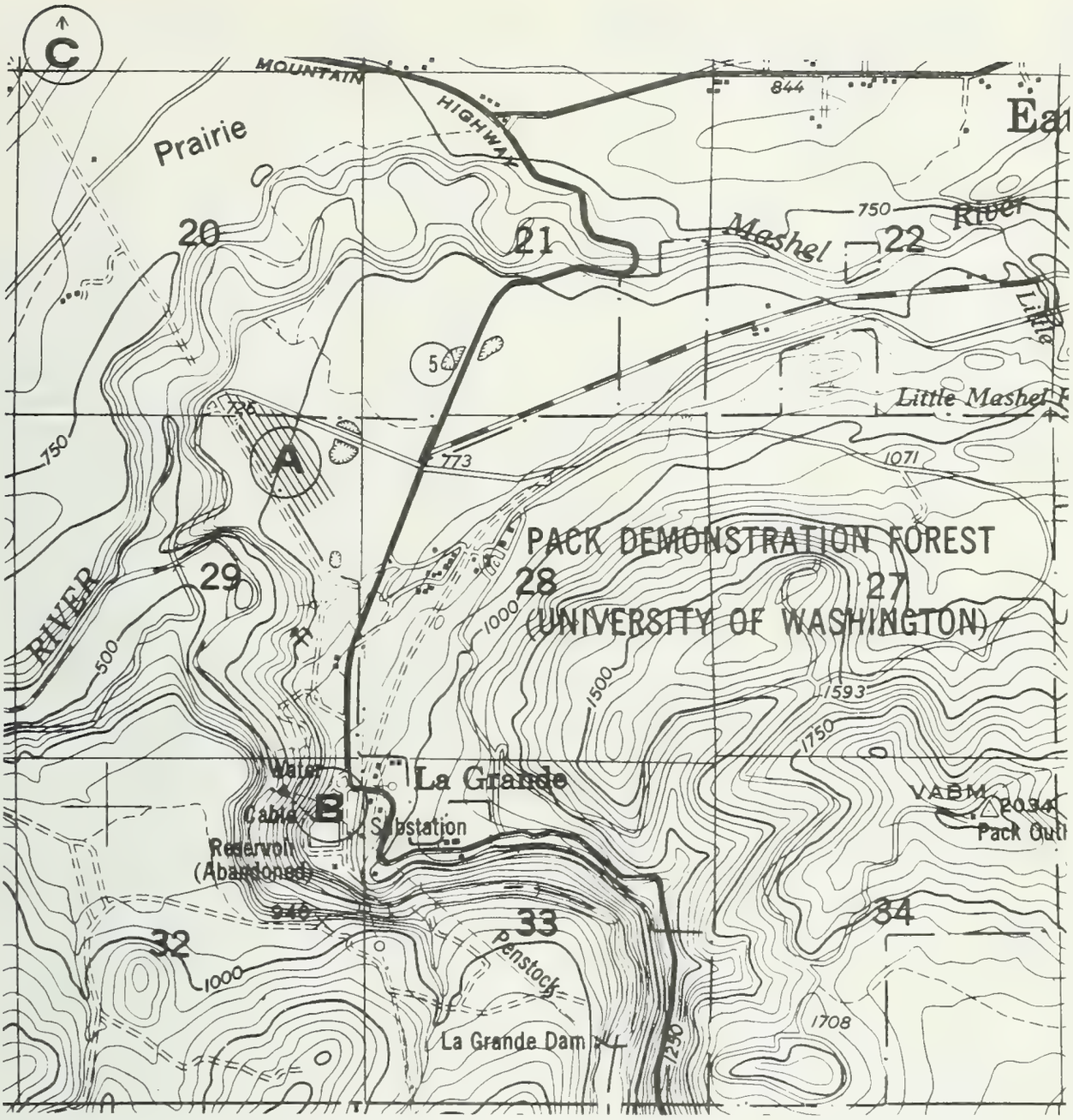


Figure 2. — Topography of Pack Forest area. The experimental site is at A and the remote camera sites are at B and C. Note that elevations are in feet m.s.l.

3.1.2. PILE BURNS

Two cone-shaped piles, each 6 meters in diameter at the base and 3 and 6 meters in height, respectively, were prepared by hand stacking from approximately 0.81 hectare of slash on the northern portion of the 12.1-hectare clearcut. These piles consisted mainly of larger material, i.e., material greater than 2 centimeters in diameter, and were burned on July 11, 1968.

3.1.3. CANADIAN FIRE

The Canadian Department of Forestry and Rural Development, under the leadership of Bob Henderson, Fire Research Officer, Victoria Laboratory, Victoria, British Columbia, was conducting research on prescribed burns in an area north of Mission City, British Columbia. Several attempts were made to monitor the smoke from these prescribed burns. However, the unseasonably wet

weather and logistics problems prevented monitoring of more than one fire. The monitored fire did not burn as planned and the data obtained are not worth inclusion in this report.

3.1.4. LABORATORY FIRE

Samples of Douglas-fir *(Pseudotsuga menziesii),* western hemlock *(Tsuga heterophylla),* and western redcedar *(Thuja plicata)* slash collected from Pack Forest area shortly after the field burns, were sent to Dr. Ellis Darley[5] for laboratory analysis of combustion products. The results of these laboratory burns were compared with those obtained under field conditions to determine the necessity for further field studies of pollutant emissions from slash fires. The system utilized for combustion and analysis is described by Darley et al. (1966).

3.2. Fuel Survey

3.2.1. FUEL WEIGHT

The quantity of fuel on the 7.45 hectares used for the broadcast burn was estimated with a line intersect method similar to that used by Beaufait.[6] The 89 sample plots were established and measured during the summer of 1967. Postponement of the experiment to the summer of 1968 necessitated resurvey of the original plots prior to the burn. Material remaining on the ground after the burn was estimated by the same method.

Sample points were established in a grid on 30-meter centers by use of 1-meter concrete reinforcing rods driven vertically into the ground. Vertical transects were established at each sample point by a horizontal meter stick mounted on top of a staff compass at the reinforcing rod point. The direction of the meter stick was chosen as follows: 6 azimuths from 0° to 180° at 30° increments were assigned to the face of a die. The die was spun at each sample point and the meter stick was aligned to the corresponding azimuth with the compass. The ends of the vertical transect were located by a plumb bob dropped from the ends of the meter stick.

The total depth of slash was measured to the nearest centimeter at the ends and the middle of the meter stick. Exposure of mineral soil along the length of the transect line was visually estimated as percent of the line. Each piece of slash which intersected the transect was identified for species and classed as slash, brush, or duff. Each piece was counted into one of three size classes, 0 to 1 centimeter, 1 to 10 centimeters, and greater than 10 centimeters. The diameter of each log larger than 10 centimeters was measured to the nearest centimeter. Duff consisting of dried or decaying needles and twigs was measured to the nearest centimeter at each of three positions, ground level, midheight, and the top of the slash. The diameter of each piece of slash less than 1 centimeter was recorded on each of ten 1-meter transects. The diameter of each of these from 1 to 10 centimeters was recorded on four transects. These measurements were used to compute the average cross-sectional areas for these two size classes as shown in table 1. Samples of the various brush species were checked throughout the burned area. The average cross-sectional area was estimated at 0.071 square centimeter. The number of pieces of 0- to 1-centimeter and 1- to 10-centimeter material in all transects was multiplied by the average cross-sectional area of these diameter classes for an estimate of the total area in each class. The area of material greater than 10 centimeters in diameter was computed from the plot data. Depth of duff was averaged for all plots. These figures were used to compute the volume of fuel on the 1-meter-square area bisected by each transect:

$$V = 100\,C(\pi/2L)$$

where V is the fuel volume in $cm.^3 m.^{-2}$; C is the total cross-sectional area of the material in square centimeters; L is the total length of the transect in centimeters; and $\pi/2$ is the elliptical correction for the slash crossing the transect plane at other than right angles (Van Wagner 1968).

The resulting averages were used to compute the total fuel volume and weight on the 7.45 hectares as shown in table 2.

The bulk density of the duff taken from the burn area was found to be 0.04 gram per cubic centimeter ($g.cc.^{-1}$). The slash material was assigned a density of 0.40 $g.cc.^{-1}$, based on the values for ovendried Douglas-fir as given by "Wood Handbook" (USDA Forest Products Laboratory 1955).

The amount of material remaining after the June 25 fire was estimated on 22 plots by the

[5] Dr. Ellis Darley, Statewide Air Pollution Research Center, Riverside, Calif.

[6] Personal communication. Dr. William Beaufait, Northern Forest Fire Laboratory, Missoula, Mont.

Table 1.—*Calculation of average cross-sectional area for material in two diameter classes, broadcast fire, Pack Forest, June 25, 1968*

0- to 1-centimeter diameter class	Number of pieces	Total area	1- to 10-centimeter diameter class	Number of pieces	Total area
		Cm.^{2}			*Cm.*^{2}
0.1	186	111.4601	1	44	34.5400
.2	653	20.5042	2	10	31.4000
.3	265	18.7222	3	1	7.0650
.4	130	16.3280	4	2	25.1200
.5	63	12.3637	5	4	78.5000
.6	28	7.9128	6	0	—
.7	21	8.0776	7	0	—
.8	16	8.0384	8	0	—
.9	15	9.5377	9	0	—
			10	0	—
	1,377	102.9448		61	176.6250
	$c = \frac{102.9448}{1377} = 0.0748$ cm.^{2}			$c = \frac{176.625}{61} = 2.8955$ cm.^{2}	

Table 2.—*Weight and volume of fuels on the ground prior to broadcast burn, Pack Forest, June 25, 1968*

Size of material	Number of pieces	Total area	Volume per plot	Weight per plot	Weight for 7.45-hectare burn	
		Cm.^{2}	*Cm.*^{3}	*Grams*	*Metric tons*	*Short tons*
Duff	(5.53)[1]		55,300	2,212	164.79	162.0
0-1 cm.	15,435	1,154	2,038	815	60.72	59.7
1-10 cm.	653	1,890	3,337	1,335	99.46	97.9
10 cm.	34	6,330	11,147	4,459	332.20	326.9
Brush	1,559	110	194	78	5.81	5.7

[1] Average depth of duff on all plots.

same sampling methods. Exposed mineral soil was estimated on 45 plots as percent of transect length. Brush was unrecognizable as such and was included with the slash material. Density was assumed to be the same. Fuel in the 0- to 1-centimeter size class was almost completely consumed by the fire. The average cross-sectional area was assumed to be 0.5 square centimeter. The average cross-sectional area in the 1- to 10-centimeter size class was found to be 23.9 square centimeters on the basis of 24 measurements. The results are shown in table 3.

3.2.2. FUEL MOISTURE CONTENT

Samples of each type and diameter class of slash were collected from each sample point the day before the fire, because firing grenades were placed in the slash area the morning of the burn. Weather conditions affecting fine-fuel moisture were comparable on both days. These samples were stored in polyethylene bags at -5° C. until moisture content determinations could be run.

Moisture content determinations were to be made with a Carl Fisher apparatus; however, no satisfactory technique for handling milligram subsamples was found which would allow for the large intrasample variations in these samples. Consequently, moisture content determinations were made on a pilot basis by use of weight loss after drying at 105° C., weight loss after vacuum ovendrying, and toluene distillation. After the initial pilot runs, the vacuum oven technique was chosen as the best compromise between repetition and analysis time.

3.3. Ignition Techniques

3.3.1. BROADCAST FIRE

Since engineers participating in the study of the clearcut block burn were studying energy exchange, a quickly ignited fire with a high rate of energy release was desired, because one dominant convection column with basal air entrainment was required. A secondary factor affecting the ignition strategy was the large amount of green fuel present on the block because of the 1-year "layover" of slash. Green bracken fern, salal, trailing blackberry, hopclover, geranium, and other herbs and short shrubs made up a nearly complete green ground cover 25 to 60 centimeters tall. Considerable heat output would be necessary to overcome the high moisture content of this live fuel element.

An electrical ignition system with an areally distributed fuel booster was used to obtain the quick hot fire. This type of ignition and burning strategy is occasionally used on better planned prescribed burns in the forests of central and northern California and the Pacific Northwest[7] (Reifsnyder 1956; Schimke and Dougherty 1966). Because the fuel was sparse and discontinuous on the northwest one-third of the block, the experimental team decided to confine the burn to the southeasterly 7.45 hectares.

[7] See also: USDA Forest Service. Use of electric starters on Hobo Block 25. St. Joe National Forest. 1966. (Unpubl. report, St. Joe National Forest, St. Maries, Ida.)

Table 3.—*Weight and volume of fuels remaining after broadcast burn, Pack Forest, June 25, 1968*

Size of material	Number of pieces	Total area	Volume per plot	Weight per plot	Weight for 7.45-hectare burn	
		Cm.^{2}	*Cm.*^{3}	*Grams*	*Metric tons*	*Short tons*
Duff	(2.71 cm.)[1]		27,100	1,084	80.76	79.5
0-1 cm.	41	20.5	58	23	1.71	1.7
1-10 cm.	39	932.1	2,662	1,065	79.34	78.1
10 cm.	23	4,614.0	13,345	5,338	397.68	391.4

[1] Average depth of duff on all plots.

Four hundred and twenty ignition points were systematically located over the slash area. One central line of ignition points extended down the middle of the rectangular burning unit (fig. 3). Three rings of ignition points were also placed — the innermost ring 15 meters from the centerline; the middle ring, 45 meters; and the outside ring, 83 meters or 7.5 meters from the outside edge. The outer two rings were split into two separate circuits because of high accumulated resistance.

The circuits were wired in series (rather than parallel) because voltage force can be calculated more readily and because less wire is necessary which reduces the cost. An ohmmeter was used for constant field checks of resistance and continuity of circuits. A total of 5,486 meters of aluminum wire was used for the electrical circuits. Aluminum wire was used because it would melt at temperatures expected during the slash burn, and it would not have to be retrieved afterwards to prevent injury to test personnel or wildlife. A jellied fuel, identical to napalm, was used as the fuel booster package at each ignition point.

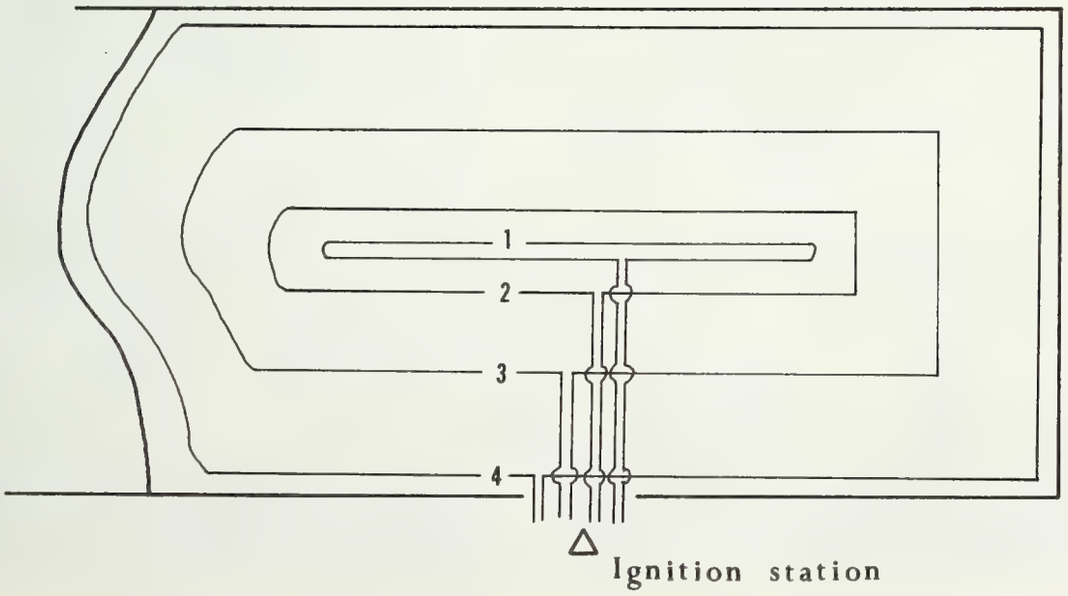
The central ignition line and the northwesterly end of the block were fired with 1.06-liter grenades. Greater heat output was judged necessary at this northwesterly location because of the large amounts of green fern, herbs, and brush with high, live-fuel moisture. Plastic packages filled with the fuel booster, called "blivets," 0.78 liter in volume, were used for all of the remaining ignition points. The thickened napalm was used because preliminary tests showed it to have the following advantages:

1. Easy to ignite.
2. Sustained, hot flame: 7×10^6 calories (28,000 B.t.u.) heat content per 453 grams (1 pound) and an approximate burning temperature of 770° C. (1,400° F.). Other fuel boosters in use (i.e., petroleum gels) have a heat value of approximately 4.5×10^6 calories (18,000 B.t.u.) per 453 grams and burning temperatures of 440° C. (800° F.) (Schimke and Dougherty 1966). The napalm fuel booster units burn longer (6-10 minutes) than any other incendiary device used in forest fire operations (Dell and Ward 1967).
3. The fuel will not flash off.
4. Manufacturers claim the fuel residue is not injurious to human or animal life.

A total of 249 kilograms of the jellied fuel was used. Black powder squibs and spitter fuses were the ignition source. A 50-cap condenser-type blasting machine was used as the power source.

The central circuit was ignited first. Then each ring or half ring was ignited 2 minutes apart with the peripheral ring ignited last. The firing strategy was planned to produce the central convection column and basal air entrainment required for the study.

Figure 3. — Electrical ignition plan of the broadcast fire on Pack Forest, June 25, 1968. Circuits 1, 2, 3, and 4, as shown, were fired in that order.



3.3.2. PILE FIRES

The piles were ignited around the base with standard drip torches filled with a 3:1 mixture of diesel fuel and gasoline.

3.4. Emission Analysis

3.4.1. SUSPENDED PARTICULATE MATTER

3.4.1.1. Ground sampling. — Particulate emissions were monitored continuously by high-volume, air samplers located near the downwind perimeter of the fire. Suspended particulate matter was collected on glass fiber, high-volume filter mats (MSA CT-75428).

The particulates from the high-volume filters were extracted with benzene in a Soxhlet extractor. The extract was analyzed by a gas chromatograph and mass spectrometer combination employing a 15 meter SE 30 column.

3.4.1.2. Airborne sampling. — Particulates in the smoke plume were determined as the light-scattering coefficient measured with an airborne version of the continuous integrating nephelometer developed under this grant (Ahlquist and Charlson 1968). The light-scattering coefficient and air temperature were measured and recorded simultaneously by means of a special digitizing circuit and a four-track portable tape recorder. Air pressure (altitude) was recorded on the third track and the fourth track was used for voice recording of the observations.

The resulting magnetic tape data from each sounding was plotted directly with a Leeds and Northrup XY plotter. These results were converted to micrograms per cubic meter following the method of Charlson et al. (1968) and plotted with potential temperature versus altitude.

3.4.2. CARBON MONOXIDE AND CARBON DIOXIDE

3.4.2.1. Broadcast fire

3.4.2.1.1. Ground sampling. — The air samples were taken at two locations: flame gas samples from the immediate vicinity of the flames and smoke samples at ground level near the downwind perimeter of the fire.

Two special sampling techniques were developed for this project, one for sampling flame gases and the other for sampling smoke on the ground without the benefit of electrical power.

Samples of flame gases from within the actual fire were obtained by a technician wearing an asbestos suit. The samples were collected in an evacuated 1,000 milliliter boiling flask fitted with a 90° connecting tube and a stopcock with a tapered ground-glass joint (Kimax 45000). These flasks were supported on a metal probe which also carried a thermocouple for measurement of the flame temperature.

The distribution of the gases downwind from the fire was mapped by use of the water displacement air sampler developed for this project.[8] This sampler was used primarily to determine the carbon monoxide and carbon dioxide concentrations. However, hydrocarbon gases were identified and measured from the samples taken with this device during the broadcast fire on June 25. Changing the samplers periodically during the course of each fire gave a time sequence of gaseous emissions throughout the fire. These samplers could be adjusted for a period ranging from 6 minutes to 2 hours and provided an automatic integration over the sample period. These samplers were located as shown in figure 4 for the June 25 broadcast fire.

Grab samples of smoke were obtained from the fire perimeter and also within the plume from the instrumented aircraft. These samples were collected by use of evacuated oxygen breathing tanks and a Mylar bag which was filled by means of a rubber squeeze bulb (Breysee and Bovee 1966).

Spot analyses of carbon monoxide concentrations were made with Monoxor Chemical Detector tubes. The concentration of hydrocarbon gases was also spot checked with a Johnson-Williams Combustible Gas Detector, Model SSP.

The concentrations of carbon monoxide and carbon dioxide were measured in the water-displacement air samplers by Beckman nondispersive infrared gas analyzers operated in series. The analytical train is shown in figure 5. Water vapor and particulates were removed by a Dryerite

[8] Pickford S., Charlson, R., and Buettner, K. J. K. A water-pump air sampler for use at remote sites. (In preparation for publication, USDA Forest Serv. Pacific Northwest Forest & Range Exp. Sta., Portland, Oreg.)

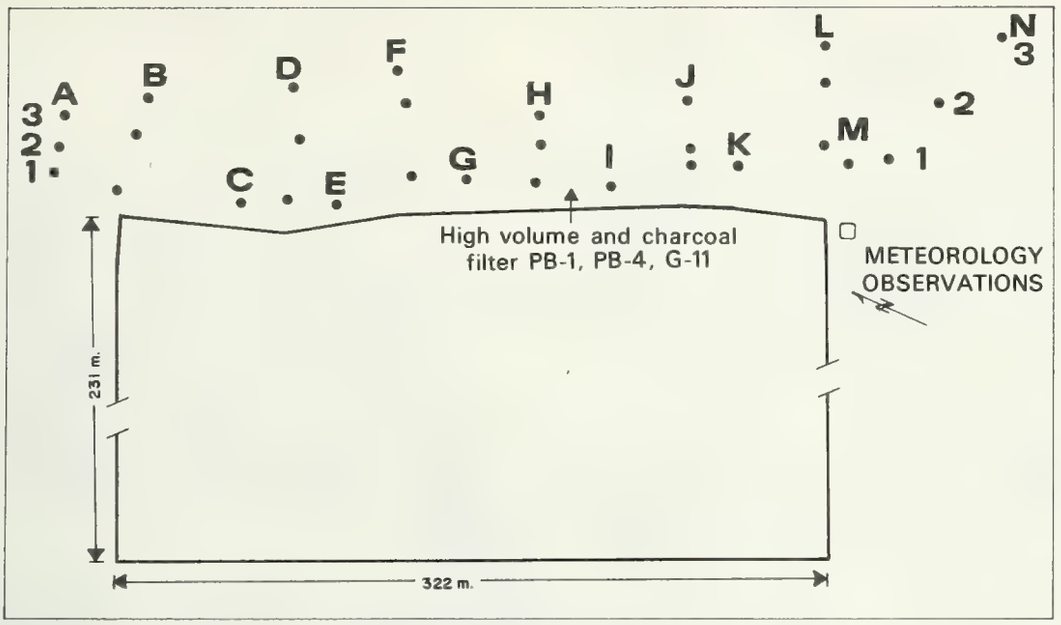


Figure 4. — Location of water-displacement air samplers, other samplers, and meteorological observations for broadcast fire, Pack Forest, June 1968. Sampling lines are numbered 1, 2, and 3, and locations on each line are represented by letters.

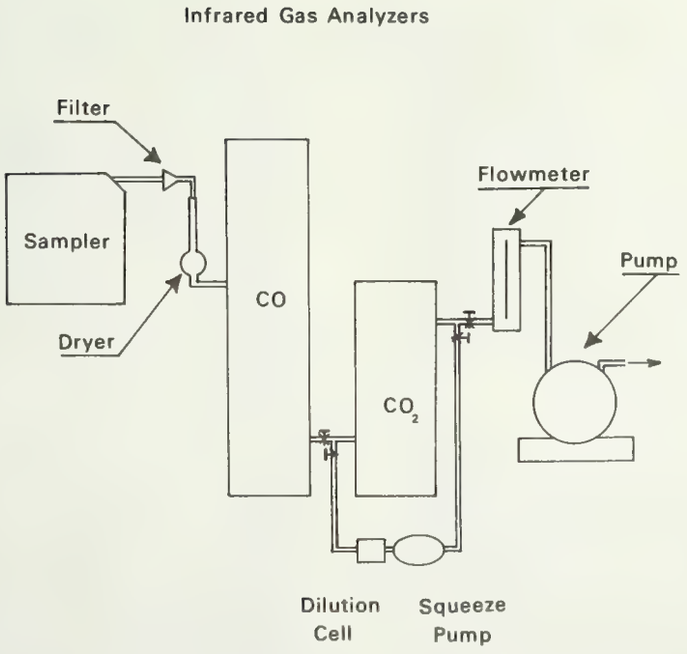


Figure 5. — Analytical train for CO and CO_2 analysis.

tube and a 41-millimeter glass mat in-line filter. The dried and filtered sample was analyzed for carbon monoxide concentrations on a Beckman 315, 0 to 100 p.p.m. (parts per million) long path, carbon monoxide analyzer. The outlet of this analyzer was connected directly to the inlet of the Beckman 215A, 0 to 600 p.p.m., short path, differential carbon dioxide analyzer using dry nitrogen in the reference cell. Varying the inlet control of the vacuum pump maintained the flow rates through the system at 50 milliliters per minute.

Gas samples were diluted when the carbon dioxide concentration exceeded 600 p.p.m. The dilution apparatus consisted of a 50-millimeter length of 76-millimeter tubing connected in series with a rubber squeeze bulb pump. The sample was shunted from the carbon monoxide analyzer through the dilution train, and when full, the train was closed. The carbon dioxide analyzer was then flushed with dry nitrogen, and the dilution system containing the sample was reconnected to both the inlet and the outlet of the analyzer. The nitrogen in the sample cell was mixed with the sample air by a squeeze pump. An accurate dilution factor was obtained by calibration of the dilution system with 370 p.p.m. carbon dioxide in air. This dilution factor was applied to the measured concentration to give the original concentration of carbon dioxide in the system.

The samples taken from within the fire were analyzed with the same system. A much higher concentration of carbon monoxide and carbon dioxide required a dilution factor of 83.331 which was obtained by replacement of the 76-millimeter tubing in the dilution train with a 19-liter carboy and operation of the dilution system in a closed path circuit through both analyzers. The dilution system was calibrated with dry nitrogen containing 250 p.p.m. carbon monoxide and compressed air containing 370 p.p.m. carbon dioxide.

The contents of the sample flask were at less than atmospheric pressure due to the difference between the collection and analysis temperatures. Each flask was brought to ambient pressure by the addition of dry nitrogen. The concentration of the diluted gas was measured with the analytical train, and the true concentration of the original gas then was calculated from the known flame temperature. By an assumption that the pressure change within the sampler was due entirely to the difference in temperatures, the correction equation simplified to:

$$Xt = \frac{(T_1)}{(T_2)} X_o$$

where, Xt is a true concentration, X_o the measured concentration, T_2 is the gas temperature at time of analysis in degrees kelvin, and T_1 is the flame temperature when sampled in degrees kelvin.

3.4.2.1.2. Airborne sampling. — Smoke samples were taken within the plume by personnel in the instrumented aircraft. These samples were analyzed for CO and CO_2 with a Beckman Ir-4 infrared spectrophotometer fitted with a 10-meter gas cell.

3.4.2.2. Pile fire. — Smoke samples from the plume of only one of the pile fires burned on July 11 were obtained by the water-displacement air samplers suspended in the plume about 12 meters above the ground. Lines thrown across the tight-wire were used to raise and lower the air samplers as shown in figure 6. The gas samplers were analyzed as described in section 3.4.2.1.1.

3.4.3. HYDROCARBON GASES

3.4.3.1. Broadcast fire. — Contaminants in several of the air samples were concentrated by freezeout at liquid nitrogen temperatures and analyzed by a combined gas chromatography-mass spectrometry technique (Bovee et al. 1966). A Varian-Aerograph Model 1200 gas chromatograph using the flame ionization detector was equipped with a 3.05-meter stainless steel Porapak Q column. Temperature was programed from 40° to 220° C., and the range of analysis extended from ethylene to xylene. A splitter placed just ahead of the detector directed part of the column effluent to a Perkin-Elmer Hitachi RMU-6D mass spectrometer. A mass spectrum was recorded for each chromatograph peak plus additional spectra for compounds not detected by the flame ionization detector. Hydrocarbon gases were also monitored continuously throughout the broadcast fire on June 25. These gases were collected on a charcoal filter which was operated from 1330 to 1800. The material collected on the charcoal was desorbed under vacuum, collected in a liquid nitrogen freeze trap, and analyzed by gas chromatography and mass spectrometry.

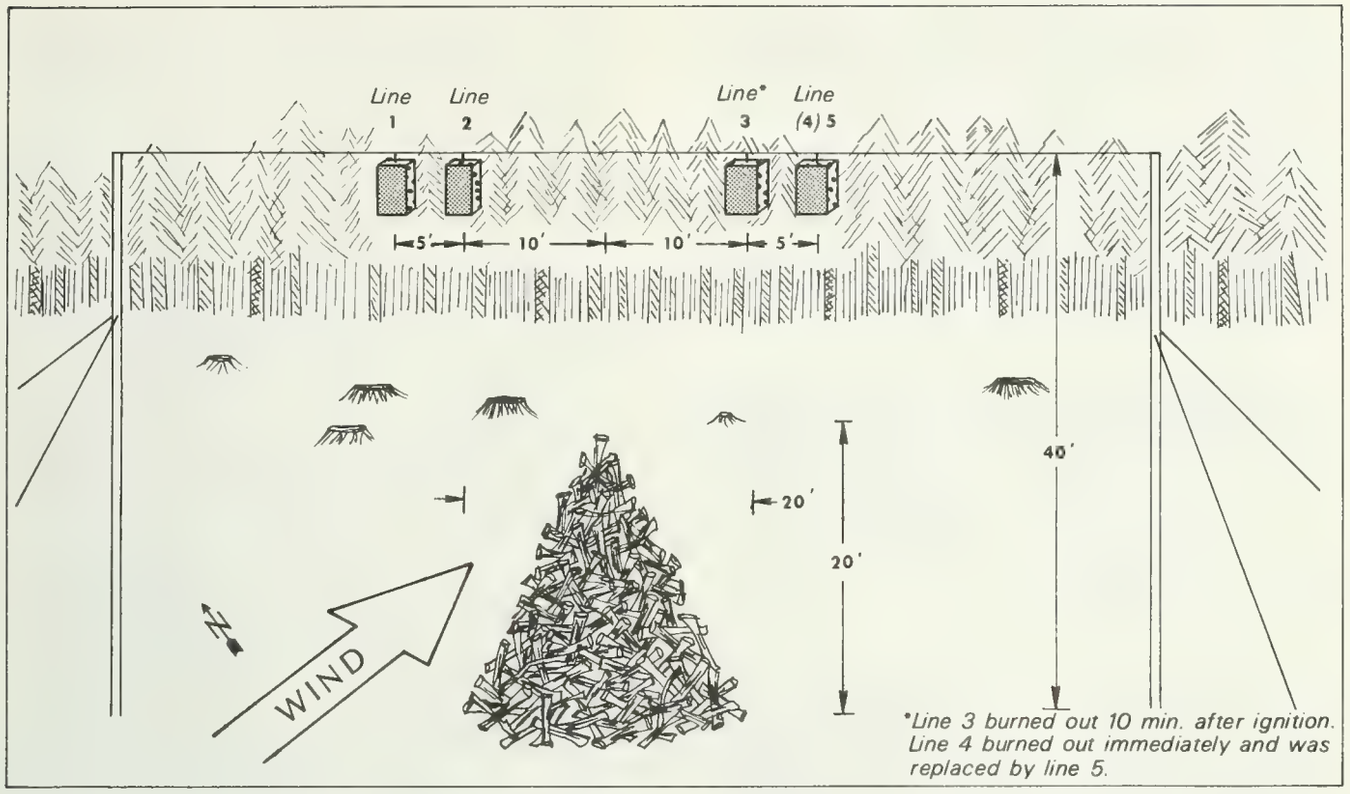


Figure 6. — Location of water displacement air samples for pile fires, Pack Forest, July 11, 1968.

3.5. Photography

3.5.1. BROADCAST FIRE

Closeup and distant photographs were taken for study of the action of the flames and the intensity of the fire and for study of the buildup and smoke migration. For the closeup pictures, a 16-millimeter movie camera was located at each of the four corners of the fire. The cameras were adjusted to take a frame every 10 seconds, viewing the fire at right angles from two sides, the north and the south.

The distant cameras were located 3.8 kilometers to the north and 1.4 kilometers to the south. These were 16-millimeter movie cameras adjusted to expose one frame every 10 seconds. In addition, another 16-millimeter movie camera was used to take continuous pictures of the fire development from the instrumented aircraft. Also, 35-millimeter slides were taken sequentially of ignition and fire buildup, smoke characteristics, and all test operations.

3.5.2. PILE FIRE

Two 16-millimeter movie cameras, mounted to obtain pictures at right angles to each other, photographed the pile fires. The cameras were operated continuously for short periods upon two-way radio command. Still cameras took 35-millimeter slides of fire and smoke behavior and test operations.

3.6. Meteorological Observations

Instrumented towers, located on the southeast and the north-central portions of the broadcast area, monitored meteorological conditions during the broadcast fire. The north-central tower carried an anemometer and wind vane, mounted at 13.7 meters to indicate the upwind conditions, but it was not functional during the fire. The southeast tower was 22.9 meters tall. Psychrometers and anemometers, mounted at 1.5, 4.6, 9.1, 13.7, 18.3, and 22.9 meters above the ground, monitored downwind conditions. A wind vane was

mounted on top of the tower. The signals from these sensors were recorded at 1-minute intervals on an automatic data-logging system. Due to the slope of the fire site, the base of the southeast tower was 3 meters below the fire level.

General meteorological conditions were also monitored at the ignition site (4.1.1).

Because of the failure of the upwind tower, upwind and downwind comparisons are not available.

4. RESULTS AND DISCUSSION

4.1. Broadcast Burn

4.1.1. FIRING TECHNIQUES

Ignition time was at 1338, June 25, 1968. Weather measured at the ignition station is shown in table 4. Within 15 minutes, a strong central draft formed and all ground level smoke flowed into it (4.1.4). The strong ground indraft was strengthened on the north and west sides by the NNW. prevailing wind. The smoke plume pierced a fairly pronounced inversion (detected by research aircraft) extending from 640 to 914 meters over the fire. The smoke plume rose to approximately 1,370 meters and sheared to the SSE. where it encountered the strong upper-level inversion base and drifted well away from the fire area.

By 1-1/2 hours after ignition, only disorganized small sources of smoke remained. In the absence of the strong convection column, this smoke drifted and diffused at low elevations. By 2-1/3 hours after ignition, little smoke was visible over the entire unit.

Fire control was not a problem. Although the fire was extremely turbulent, no spot fires occurred in the adjoining uncut stand, primarily because of the strong central convection column with the accompanying strong indraft at the edges of the burn: Firebrands were transported upward in the convection column where burnout ultimately occurred.

The thickened or gelled napalm used as the fuel booster on the clearcut burn has the trade name "Burnol." The manufacturers could not supply the chemical composition of this specific product; however, analysis made in Fontana, Calif., and at

Table 4.—*Weather measurements*[1] *at ignition station, broadcast burn, Pack Forest, June 25, 1968*

Time	Cloud cover	Temperature		Relative humidity	Wind	
		Wet	Dry		Direction	Velocity
		Degrees C.	*Degrees C.*	*Percent*		*Meters/second*
1050	0.1	19.4	25.8	56	NNW.	0.4-4.0
1210	.1	20.0	27.8	48	NNW.	.4-2.6
1315	.1	21.4	30.0	46	NNW.	1.7-5.2[2]
1430	.1	21.6	30.0	46	NNW.	1.7-4.3

[1] June 23 and 24 were sunny and warm. Seattle-Tacoma Airport reported 27° C. the afternoon of June 24, 1968.

[2] Gusts to 6.1.

the University of Washington as part of this study is shown in the following tabulation:

Compound	Percent	
Chevron gasoline (low octane)	94	100
Activating compounds	6	
Silica aerogell (devolatilized)	5	100
Aluminized soap[1]	95	
Organic acids from cocoanut oil (extracted copra oil) tri myristin, tri laurin, tri palmitin, tri stearic	50	100
Naphthalic acid	25	
Oleic acid	25	

[1]Traces of glycerides detected.

Calculated emissions from the fuel booster, total combustion assumed, are shown in table 5. When compared with the results of Darley's laboratory tests of cellulose fuel (section 4.3.2), the fuel booster could account for 11 percent of total CO (wood fuel plus fuel booster) and 3 percent of total CO_2 emitted during the clearcut burn.[9] Each fuel booster package achieved burnout in 7 minutes, according to averages obtained from burning tests of 12 packages. Total fuel booster burnout thus occurred 19 minutes after ignition. Total fuel booster emission was during this period.

However, during stage 1 (first hour of burning), CO and CO_2 concentrations measured by the sampling net at the ground level were low (5 and 500 p.p.m., respectively).

Hydrocarbon gases during stage 1 appear to be saturated and would not contribute appreciably to photochemical smog. These measurements are of emission from both fuel booster and woody fuel. Since the greatest plume rise occurred during this period, most emissions were carried well away from the fire area and were subject to rapid dilution. Visibility reduction was greatest during

[9]Fuel booster calculations assume total combustion and an estimated C:CO:CO_2 ratio of 2:1:7 and are not adjusted for smoke and residue as are those from Darley et al. (1966).

Table 5.—*Gaseous and elemental emission from the fuel booster used on the broadcast burn, Pack Forest, June 25, 1968*

Component	C		H		O		CO		CO_2	
	Kilogram	*Percent*	*Kilogram*	*Percent*	*Kilogram*	*Percent*	*Kilogram*	*Percent*	*Kilogram*	*Percent*
Gasoline	197.0	84.0	37.0	16	—	—	—	—	—	—
Organic fatty acids	4.8	76.0	0.9	11	0.9	13	—	—	—	—
Oleic acids	2.7	77.0	.4	12	.4	12	—	—	—	—
Naphthalic acid	2.5	6.7	<.4	4	1.1	30	—	—	—	—
Subtotal[1]	10.1	—	<1.8	—	2.5	—	—	—	—	—
Total	208.0	—	>38.0	—	2.5	—	—	—	—	—
All carbon converted to CO	—	—	—	—	—	—	461.0	—	—	—
All carbon converted to CO_2	—	—	—	—	—	—	—	—	724	—
C, CO, CO_2 produced in a 2:1:7 ratio	29.5	20.0	—	—	—	—	45.8	10	508	70

[1]Total amounts of C, H, and O in the minor components amount to 6 percent of the total material in the fuel boosters.

the early stages of the fire, and the fuel booster was responsible for some portion of smoke volume and density.

Lowry (1967) has published a physical model which is useful for estimating requirements for rise of large smoke plumes from prescribed fires. He suggests that rates of energy release are too small on most slash fires to achieve good plume rise necessary for minimization of air pollution. His model gives a basis for estimating the rate at which fuel must be burned to achieve a given plume rise under stated atmospheric conditions. Lowry's model was used to evaluate rates-of-energy release on the broadcast burn. The following measurements and assumptions were used:

Atmospheric pressure	P	=1.0 atmosphere
Gradient wind	u	=2 m. sec.$^{-1}$
Plume rise	H	=1,000 m.
Radius of plume at height times radius of burn area	r(R)	=200 m.
Radius of plume times vertical windspeed	r^2W	=2.0 x 10^5 m.^{3} sec.$^{-1}$
Dimensionless buoyancy	B	=0.2
Rate of heat generation	L	=6.8 x 10^9 cal. sec.$^{-1}$

Thus, to achieve a plume rise of about 1,000 meters, approximately 6.8 x 10^9 calories per second (cal. sec.$^{-1}$) heat release would be required.

Based on fuel consumption values from table 6, the same heat-of-combustion figures used by Lowry, observations by fire scientists assigned to the experimental burn, and integration over 2 hours of primary combustion activity, the maximum rate of energy release on the experimental burn was approximately 12.8 x 10^9 cal. sec.$^{-1}$ (fig. 7). This average release rate was achieved approximately 7 minutes after ignition and was maintained, on the average, until approximately 20 minutes after ignition. The plume rose to about 1,370 meters in spite of the inversion and, based on theoretical calculations, would have risen to about 1,830 meters had the plume not encountered the upper-level inversion.

This plume rise would not have been achieved with conventional slash burning techniques; i.e., low-temperature ignition devices, slow firing, slow and discontinuous fire development, and long burnout times. Although it is impossible to prove quantitatively from the data obtained during this study, we doubt if the smoke plume could have risen higher than the base of the low-level inversion, 600 meters without the electrical ignition and fuel booster system.

Direct costs of burning the 7.45-hectare (18.44 acres) unit were $116 per hectare or $47 per acre. These costs included the fuel booster and electrical ignition:

Item	Cost
Fuel booster	$371.76
Ignition squibs	118.50
Spitter fuse	6.00
Aluminum wire	72.20
	$568.46
Man-hours:	
Wire layout, 6 man-days	
Booster package preparation, 2 man-days	
Standby crew, 20 man-days	$287.30
	$855.76

Table 6.—*Weight changes on 7.45-hectare broadcast burn, Pack Forest, June 25, 1968*

Material	Total weight change		Change per hectare	Change per acre
	Short ton	*Metric ton*	*Metric ton*	*Short ton*
Duff	- 82.5	- 84	-11.3	- 4.47
0-1 cm. (includes brush)	- 63.7	- 64	- 8.6	- 3.45
1-10 cm.	- 19.8	- 20	- 2.7	- 1.07
> 10 cm. (1-cm. shell)	- 90.3	- 92	-12.3	- 4.90
Total	-256.3	-260	-34.9	-13.90

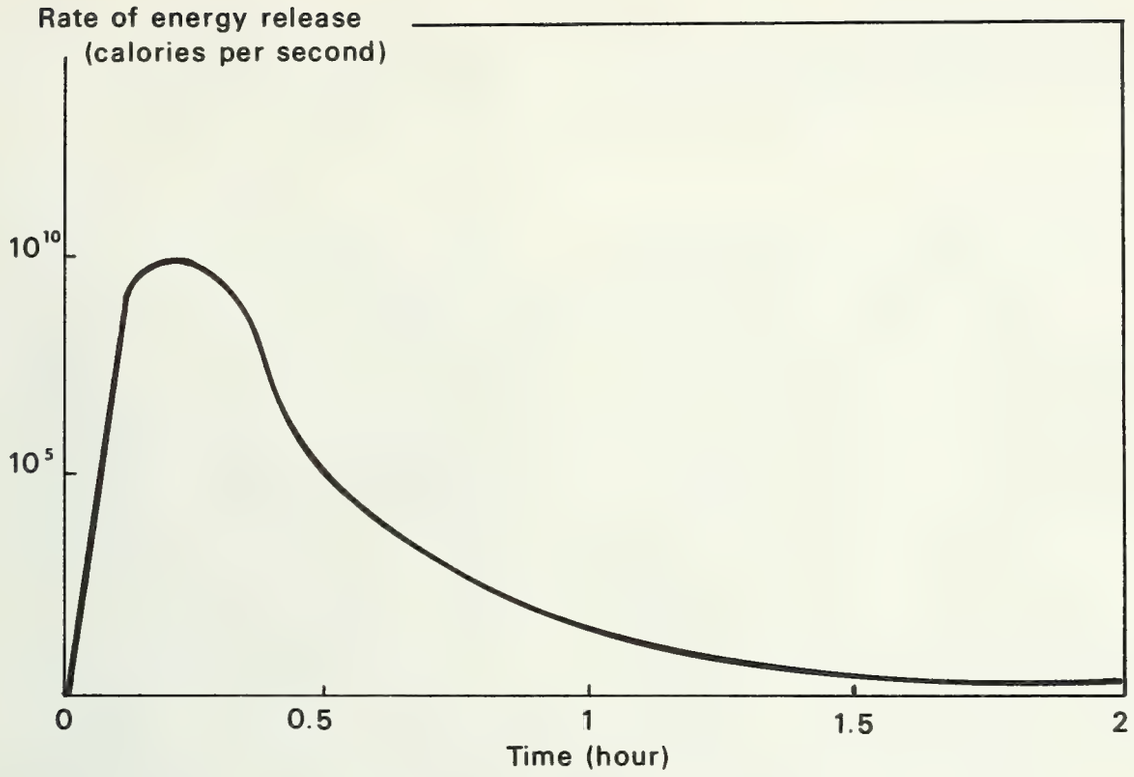


Figure 7. — Estimated rate of energy release for the broadcast fire on Pack Forest, June 25, 1968.

An adjoining 4.7-hectare unit was broadcast burned with conventional drip torches and diesel fuel. An attempt was made to obtain the same rapid rate of heat generation as on the 7.45-hectare unit. The cost of burning the smaller unit was $133 per hectare ($54 per acre). However, because the risk of wildfire was high, a 30-man standby fire control crew was used.

4.1.2. FUEL BURNED

The pre- and postfire inventories (3.2.1) were used to compute the total amount of fuel burned. The results are shown in table 6. The weight change for duff may be greater than shown. In postburn samples, no distinction was made in most cases between burned duff, unburned duff, and ashes. The weight of material greater than 10 centimeters in diameter increased after burning. This may have been due to the low sampling intensity or the bias introduced either by burial of this material by fine fuels before the fire or exposure of the material afterwards. However, only an outer shell of approximately 1 centimeter was charred on material 10 centimeters in diameter or larger. Because the amounts of material in this size class were approximately the same in both surveys, an estimate of the material which actually burned was made by computation of the volume per plot of this 1-centimeter shell and use of this figure in table 6.

Mineral soil exposed prior to the burn was estimated to be 10 percent; after the burn, 18 percent. This difference may not be statistically significant since only half of the plots were remeasured after the burn. The average duff depth before and after the fire changed from 5.53 to 2.71 centimeters. Some of the material represented as duff in the postfire remeasurement consisted only of ashes and some was partially burned. No measurements were made to determine relative proportions of ashes, burned duff, and unburned duff. However, reports by cooperating fuels scientists indicated total reduction in duff load on the area was light when the intensity of the fire was considered.[10]

[10] Fahnestock, G., and Morris, W. Unpublished report on file, Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, Portland, Oregon. June 30, 1968.

4.1.3. FUEL MOISTURE

Moisture content for each stratum of the slash material was averaged for all plots. The results are shown in table 7.

4.1.4. PHOTOGRAPHY

On the basis of time-lapse photography, the June 25 fire was broken down into three stages, each with characteristic fire and plume behavior. The first stage was characterized by fire buildup, a hot fire, and convergence and eddy mixing in the resulting convection column. This stage lasted until 1410 (section 4.1.5) and was roughly equivalent to the period I gas samples, section 4.1.6.2.

Stage II, corresponding to period II gas samples (4.1.6.2), was characterized by a general dying down of the fire, a tendency for the convection column to bend over at the ground, but with abundant fire remaining in the area. The stage II fire gradually diminished until by 1510 only scattered hotspots, i.e., campfire-size blazes, remained in the area. This was termed stage III, although it had very indefinite beginnings. Most period III gas samples were taken after the fire had reached this stage. So little fire remained in the area that most experiments other than gas sampling were terminated.

4.1.5. METEOROLOGICAL CONDITIONS

General meteorological conditions at the ignition site were given in section 4.1.1. Meteorological conditions at the southeast corner of the broadcast burn are shown in figures 8 and 9. The prevailing wind was from the northwest at about 3 meters per second (m. sec.$^{-1}$). However, during stage I, the buildup period, air flowed into the fire from all directions. This is illustrated in figure 8, between 1340 and 1410. The shaded area of wind directions indicates the period of airflow into the fire. During this period, the windspeed decreased as the air started to converge. Windspeed increased as convergence reached a maximum at 1510, then decreased as the fire started to lose energy. During stage II of the fire, the wind direction switched around to the northwest again and the velocity increased to the original level.

Air temperature substantiates the above statements (fig. 9). The inexact correlation between wind direction and low air temperatures is due to the difference in time response of the wind vane (instantaneous) and the temperatures (about 2 minutes). During the buildup, the temperature dropped as fresh air moved into the fire (fig. 9, 1340 to 1410). Air temperature increased again as the wind direction changed to the northwest,

Table 7.—*Moisture content (expressed as percent ovendry weight) of fuel on sample plots prior to broadcast burn, Pack Forest, June 25, 1968*

Material	Moisture content	Standard deviation	Range
	Percent		
Brush	190	136	7-622
Duff, ground	48	22	18-120
Duff, midtransect	28	30	5-141
Duff, top	19	15	4- 34
0-1 cm., ground	21	31	2-165
0-1 cm., midtransect	25	48	7-282
0-1 cm., top	17	12	2- 78
1-10 cm., ground	22	7	11- 49
1-10 cm., midtransect	19	8	2- 45
1-10 cm., top	23	7	10- 39

causing the heated air from the fire to reach the temperature sensors. The fire energy system obviously dominated the mesoscale weather at the burning site during the 1340-1410 period.

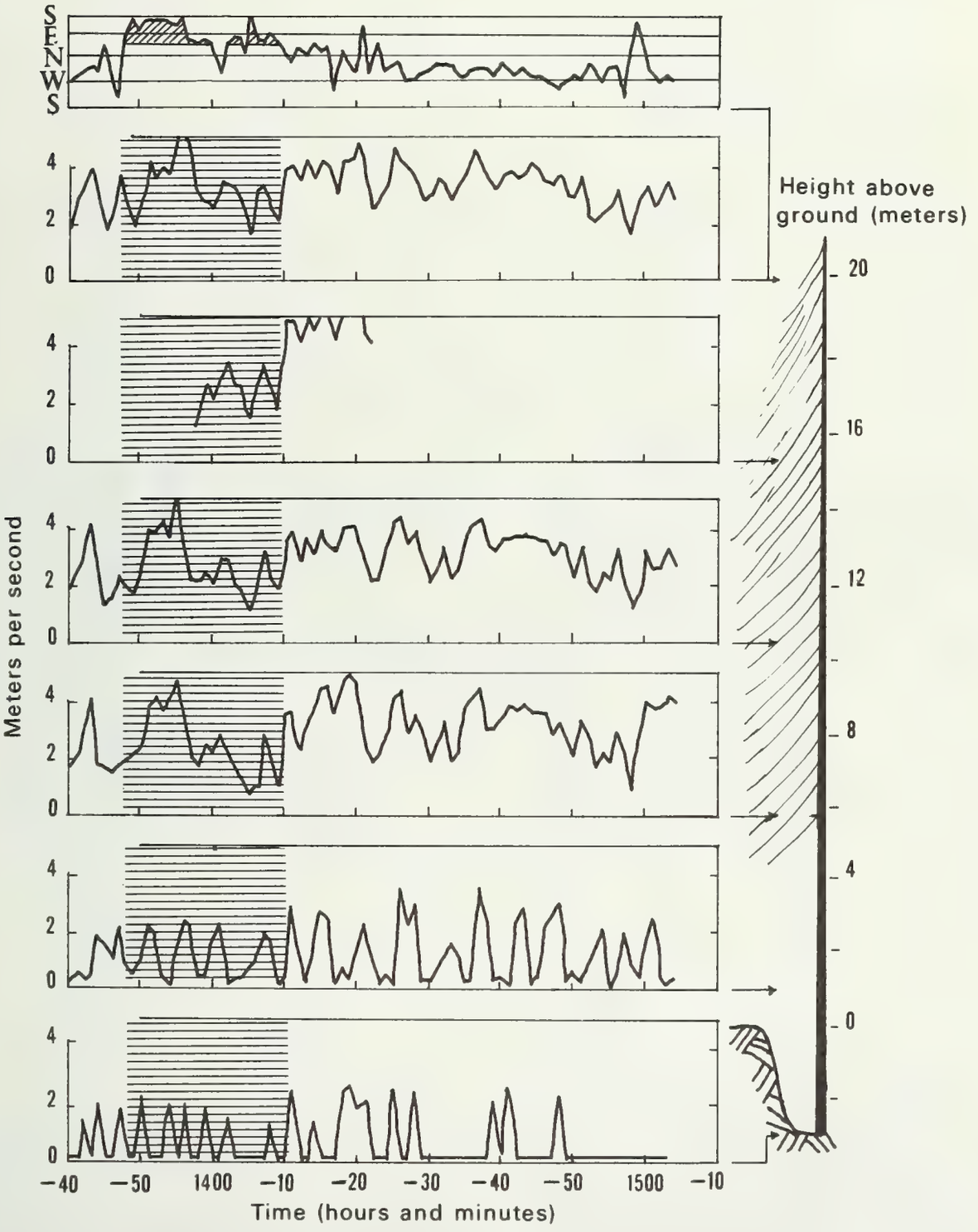


Figure 8. — Wind direction and speed monitored on the southeast corner of the broadcast fire on Pack Forest, June 25, 1968.

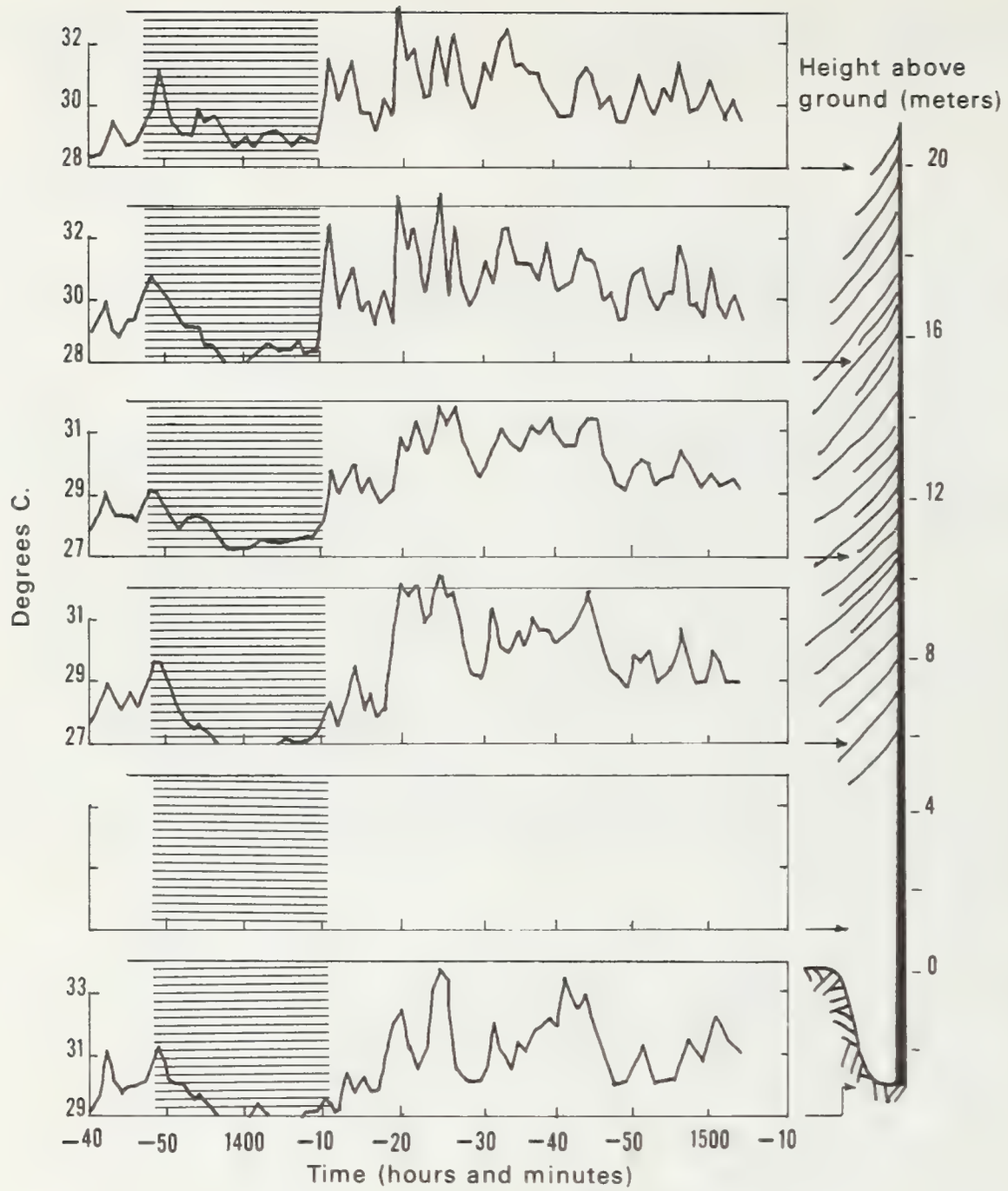


Figure 9.—Air temperatures monitored on the southeast corner of the broadcast fire on Pack Forest, June 25, 1968.

4.1.6. EMISSION ANALYSIS

4.1.6.1. Suspended particulate matter. — Gas chromatographic analysis of the benzene extracts from the high-volume filter mats showed up to 50 distinguishable peaks. Mass spectral data, obtained simultaneously, indicated the presence of alkanes, alkenes, alcohols, ketones, and essential oils.

The particulate loading and extractable percentage before and during the burning is shown in table 8. The background particulate loading was high for a rural area and probably due to slash burning on the previous day. The particulate loading increased the morning of June 25 prior to ignition. This may be due to increased vehicular traffic in the area by study personnel. At least two

Table 8.—*Particulate loading and extractable percent obtained with high volume samples before and during the broadcast slash burn at Pack Forest, June 24-25, 1968*

Material number	Collection period		Particulates	Extractable percentage
			$\mu g.m.^{-3}$	
88	1000	June 24	64	6.4
	0923	June 25		
73	0900	June 25	160	22.0
	1334			
87	1334	June 25	1,150	30.8
	1430			
86	1431	June 25	1,510	34.2
	1629			
85	1630	June 25	950	25.4
	1827			

other slash fires in the vicinity were noted by personnel in the aircraft prior to ignition. Particulate matter from these fires may also have increased the prefire background as well as the extractable percentage.

The problem of visibility reduction in the Northwest can be visualized when average particulate loadings above major U.S. cities for 1961 are compared:[11]

City	Particulates ($\mu g.\ m^{-3}$)
Chicago	190
New York City	173
Philadelphia	173
Milwaukee	146
Baltimore	142
St. Louis	141
Pittsburgh	137
Cleveland	136
Washington	128
Detroit	118
Dallas	92
Seattle	87
Atlanta	84
Miami	54

[11] From U.S. Department of Health, Education, and Welfare (1966), table 2.3.

The Northwest atmosphere is typified by good visibility and relatively low particulate loads. Thus, any increase in particulate loading and subsequent decrease in visibility, especially in the direction of the surrounding mountains, is readily noticed by both the inhabitants and news media in the area. This problem is not as severe in other areas, i.e., New York, Chicago, etc., where visibility is typically much lower.

Plume characteristics are shown by aerial soundings in figure 10. Location of each sounding is shown in figure 1. The first, 1215, was made during the flight from Seattle to the experimental site. The local industrial pollutants appear to be concentrated in the low-level inversion between 300 and 600 meters. These data are summarized in table 9. Average particulate loading prior to ignition was about the same over both the fire site and the Seattle industrial area. However, the peak loading was much greater over the industrial area. Significantly, the 1722 and 1742 particulate loadings near and over Puyallup (primarily residential and light industry) were not increased above that observed over the Seattle industrial area before the fire, even though the plumes of at least three slash fires had drifted over the area. The particulate sample periods from 1334 to 1827 in table 8 generally represent the three fire stages. Between 1334 and 1431 (stage I), particulate loading increased but the strong central convection column with horizontal inrushing winds carried most

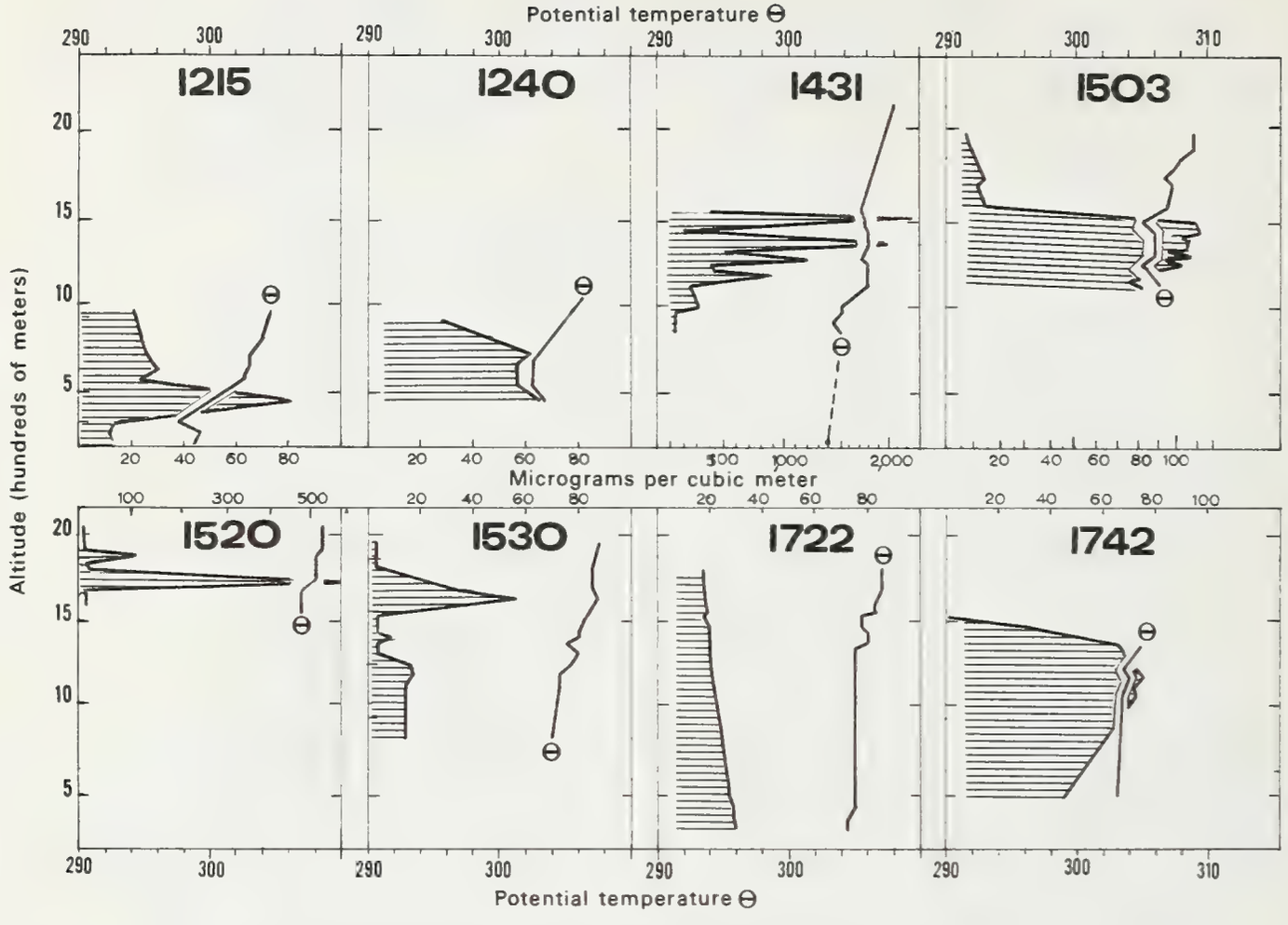


Figure 10. — Mass of suspended particulates and potential temperature observed during vertical soundings of the plume from the broadcast fire, Pack Forest, June 25, 1968.

Table 9.—*Summary of aerial particulate soundings associated with the experimental fire, June 25, 1968*[1]

Time	Location	Altitude	Particulate			Average meteorological range
			Average	Peak	Background	
		Meters		*μg.m.*$^{-3}$		*Kilometers*
1215	58 km. NE.	152- 488	48	129	30	24.0
1240	Over burn	579- 823	60	66	21	20.0
1431	3.9 km. N. 72° E.	914-1,584	690	1,980	18	1.6
1503	17.1 km. N. 60° E.	1,310-1,524	186	216	18	6.2
1530	31.9 km. N. 39° E.	1,524-1,768	123	181	12	9.5
1722	28.1 km. N. 18° E.	244-1,555	58	84	3	20.2
1742	40.2 km. N. 4° E.	457-1,494	27	75	3	43.3

[1] Refer to figure 1 for location.

of the particulates aloft. Loading was greatest during the diedown stage II (1431 to 1629) when prevailing wind carried the smoke over the sampling site. The extractable percentage also increased. Total particulates decreased in the last period (stage III) and the extractable percentage reduced to the prefire level. The 1240 sounding over the experimental site shows a pronounced inversion between 518 and 640 meters and, when combined with the 1431 sounding, illustrates the atmospheric stability.

The convection column broke through the lower inversion, reaching 1524 meters before drifting horizontally (1431). As the plume drifted away from the fire, it rose slightly from 1,524 meters to 1,737 meters and appeared to follow the 308° to 309° K. potential temperature surface. The 1742 sounding shows the particulate loading associated with two other lower energy slash fires.

The particulate loading of the plume diluted downwind. This can be shown as the meteorological range. The meteorological range is the visual range which would be observed if the air were perfectly homogeneous and is related to particulate loading by

$$\text{Meteorological range (m.)} = \frac{11.7 \times 10^5}{\mu\text{g. m.}^{-3}}$$

Meteorological range increased from 0.5 kilometer in the plume at the fire to 4 kilometers at a distance of 32 kilometers downwind. In contrast, the meteorological range varied from 25 kilometers to 100 kilometers over the Seattle industrial area prior to the burn. The meteorological range of the background air in the 1431 through 1530 soundings was about 100 kilometers.

The particulate loading appeared to be diluted by about twofold to tenfold from the ground site to the horizontal plume at the fire. When this dilution factor is combined with the CO_2 dilution factor from the fire to the ground sampling net of 40 to 60, the result would indicate a total dilution of 80 to 600 from the fire to the top of the convection column.

4.1.6.2. Carbon monoxide and carbon dioxide.— The results of carbon monoxide and carbon dioxide analysis are shown in appendix 9.1.1 for the broadcast fire and appendix 9.1.2 for the pile fire. The data for the broadcast fire are summarized in table 10.

The CO and CO_2 concentrations decreased rapidly from the fire through the sample net. Dilution of hydrocarbons and particulate matter was probably comparable. The distributions of CO and CO_2 downwind from the broadcast fire are shown as isopleths in figures 11, 12, and 13.

The concentration from the flames (table 10) to the first line of the sample net changed by a factor of about 520 to 980 for CO, and from 40 to 60 for CO_2. This may indicate that CO underwent further oxidation from the fire to the sample net.

The particulate loading changed by a factor of about 2 from the high-volume filter (period I) to the plume (1431 nephelometer sounding). The average concentration of all hydrocarbon gases changed by about the same factor as the particulate loading from station 9-1, near the high-volume filter during period I, to the airborne grab sample taken just prior to the 1431 sounding. These changes are summarized as follows:

Concentration ratios for various smoke components from broadcast fire, Pack Forest, June 25, 1968

Component	Flame:sample net	Sample net:aircraft
CO	520 – 980	83
CO_2	40 – 60	([1])
Particulates	([1])	1.67
Hydrocarbons (all gases)	([1])	2.7

[1] Unknown.

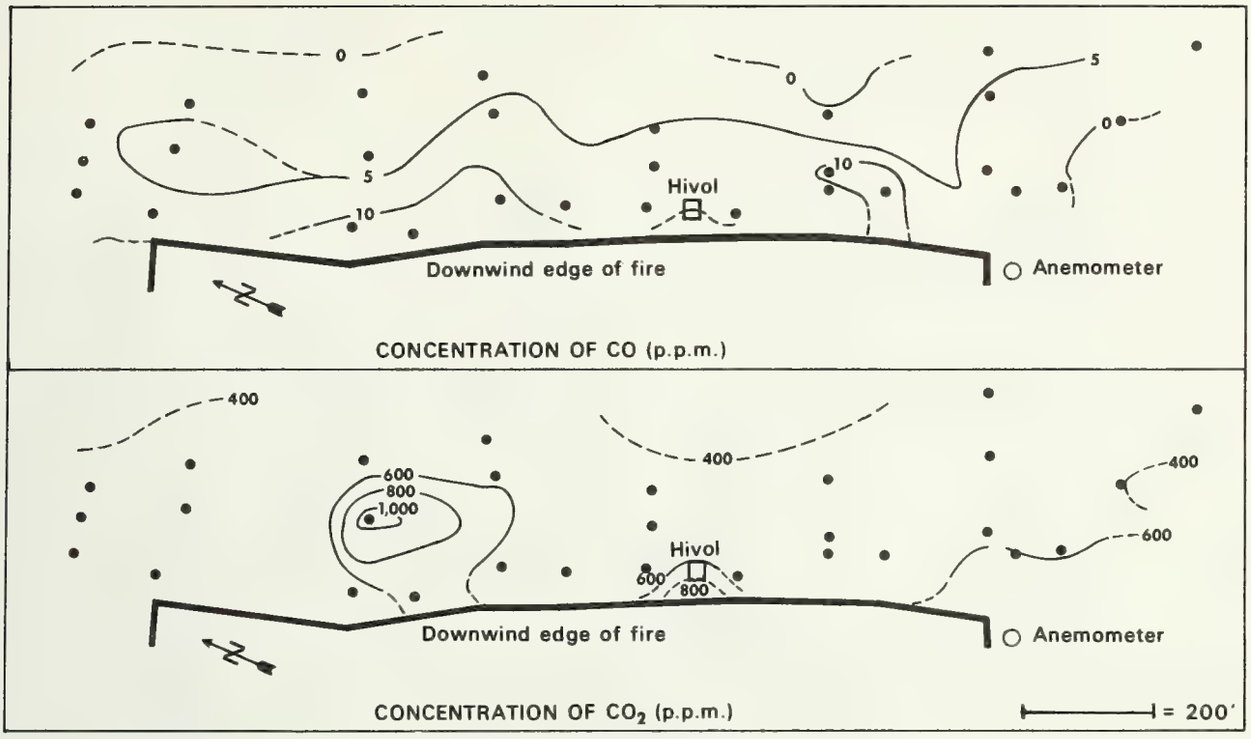
No CO was detected in the 1431 grab sample from the aircraft. The CO_2 concentration in the same sample was 330 p.p.m. The oxidation of CO may have reduced its concentration from an expected 4 p.p.m. to below the detection limit of 1 p.p.m. If both the sampling and analysis are reliable and 0.1 p.p.m. is the maximum undetectable concentration of CO, the minimum change in CO concentration from the sample net to the aircraft would be 83. This change in CO concentration is assumed to be due to oxidation. If the CO_2 concentration changed by the same factor as the particulate and hydrocarbons, the measured CO_2 concentration at the aircraft should have been 60 p.p.m. above ambient CO_2 concentrations. However, no ambient measurements were made.

This sample was taken from an aircraft flying within the plume. If it had been a true point sample, then there is a reasonable chance that the sample was taken from a pocket of unmixed ambient air within the plume. However, the tank in which the sample was taken requires about 10 seconds to fill. If the plane was moving at 40 m.sec.^{-1} (90 m.p.h.), then the sample was taken

Table 10.—*Concentration of major plume components from broadcast fire, Pack Forest, June 25, 1968*

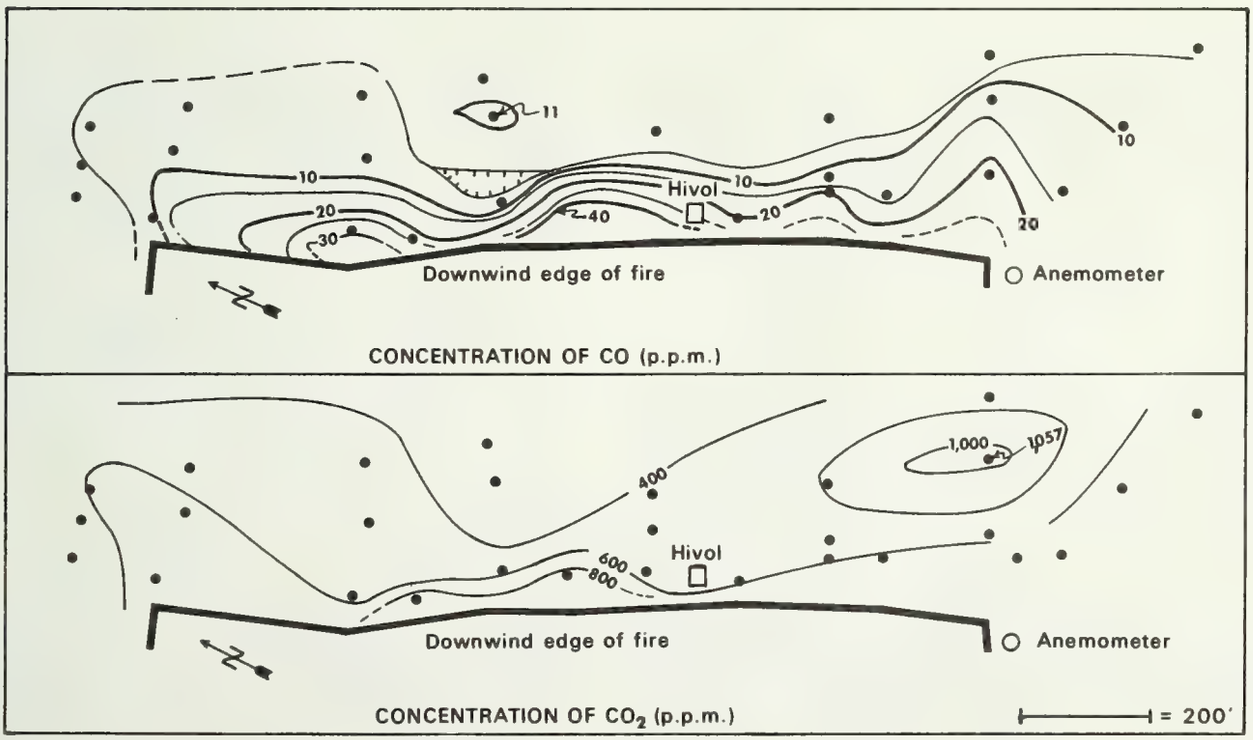
Sample	Flames			Line 1		Line 2		Line 3		Average all lines		1431 sounding (4 kilometers downwind 1,800 meters)
	850° C.	500° C.	500° C.									
	------*Parts per million*-----			*Average parts per million*	*Sd.*[1]	*Average parts per million*	*Sd.*[1]	*Average parts per million*	*Sd.*[1]	*Average parts per million*	*Sd.*[1]	*Parts per million*
CO:	917	4,315	8,104									0
Period I				8.1	3.2	5.2	3.8	5.2	2.6	6.5	3.4	–
Period II				18.7	10.3	10.0	3.3	6.8	1.1	13.8	9.7	–
Period III				6.5	2.8	7.6	.6	5.6	3.8	6.6	2.7	–
CO_2:	31,000	22,000	40,000									330
Period I				561	97	620	251	480	37	555	149	–
Period II				626	154	665	232	575	127	625	164	–
Period III				530	118	519	93	596	188	543	129	–
$CO/(CO_2^{-330})$ (average):	0.029	0.194	0.203									
Period I				0.039	–	0.024	–	0.035	–	0.034	–	–
Period II				.072	–	.036	–	.033	–	.054	–	–
Period III				.045	–	.048	–	.066	–	.051	–	–
Particulate:	–	–	–	$\mu g.m.^{-3}$								$\mu g.m.^{-3}$
Period I				1,150	–	–	–	–	–	–	–	690
Period II				1,510	–	–	–	–	–	–	–	–
Period III				950	–	–	–	–	–	–	–	–
Methane:	–	–	–									
Period I				–	–	–	–	–	–	–	–	–
Period II				2	–	–	–	10	–	–	–	2
Period III				2	–	–	–	–	–	–	–	–
Methanol (period II)	–	–	–	1.92	–	–	–	–	–	–	–	0.45
Benzene (period II)	–	–	–	.03	–	–	–	–	–	–	–	.00
Toluene (period II)	–	–	–	.40	–	–	–	–	–	–	–	.04

[1]Standard deviation.



Period I 1300–1430

Figure 11. – Horizontal distribution of CO and CO_2 during period I of the broadcast fire, Pack Forest, June 25, 1968. (Shown as isopleths.) Data indicate location of water displacement air samplers.



Period II 1430–1630

Figure 12. – Horizontal distribution of CO and CO_2 during period II of the broadcast fire, Pack Forest, June 25, 1968. (Shown as isopleths.)

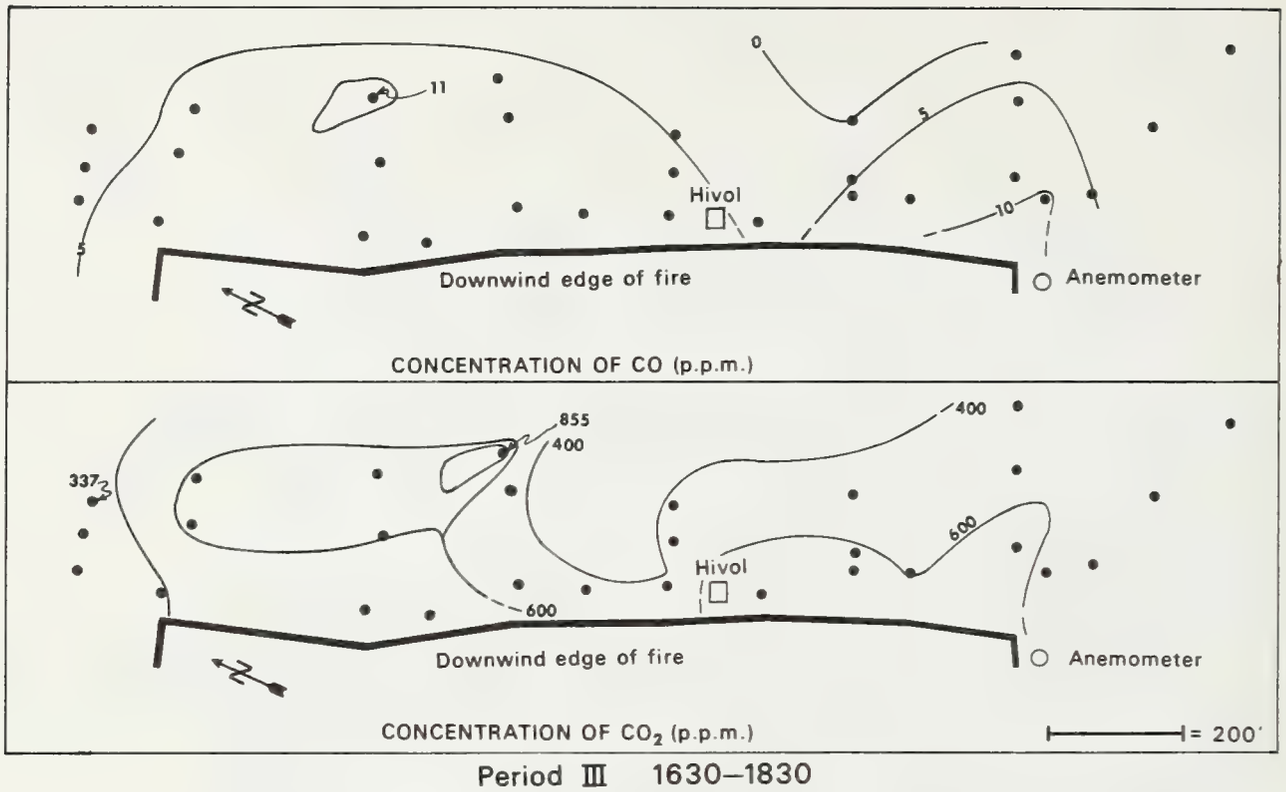


Figure 13.—Horizontal distribution of CO and CO_2 during period III of the broadcast fire, Pack Forest, June 25, 1968. (Shown as isopleths.)

over a 400-meter segment of the plume. Integration of the sample over this distance should provide detectable quantities of both CO and CO_2 if present in greater than ambient concentrations.

The change in the ratio of CO to CO_2 during the fire is apparent in figure 14. CO versus CO_2 concentration at each point in the sample net is plotted for each period. The slopes (m) of the $CO:CO_2$ ratios obtained from the 500° and 850° flame gases are indicated by the dashed lines. The smoke in period I apparently originated from flames between 500° and 850° C. However, in period II, several of the samples taken along line 1 fall very close to the slope of the cooler flame.

Ventilation was available for fuels in the interior of the burn because of turbulence associated with the stage I convection column. The gradient wind which predominated in stage II provided less interior ventilation. The better interior ventilation during period I plus the rapid consumption of flash fuels (0-1 cm.) created higher temperatures and more complete combustion during stage I. During stage III, almost all of the finer fuels had been consumed. With the exception of smoldering duff, the fire was confined to small, well-ventilated, and compact piles of heavier fuels in which flame temperatures were again higher, and combustion more complete than during stage II.

The $CO:CO_2$ ratio from the 850° flame gases approximately equals the $CO:CO_2$ ratio from laboratory combustion of Douglas-fir slash (4.3.2). This indicates that both the temperatures and the degree of combustion were approximately the same in the field during stage I and under laboratory conditions. The strong convection column of the stage I fire created return eddies which provided a strong backwind around the perimeter of the fire. The plume components during this stage therefore were transported through the sample net from line 3 (most distant) to line 1 and back to the fire. When the convection column could no longer penetrate the inversion during stage II, the gradient wind carried the plume directly across the downwind fireline and through the sample net from line 1 to line 3.

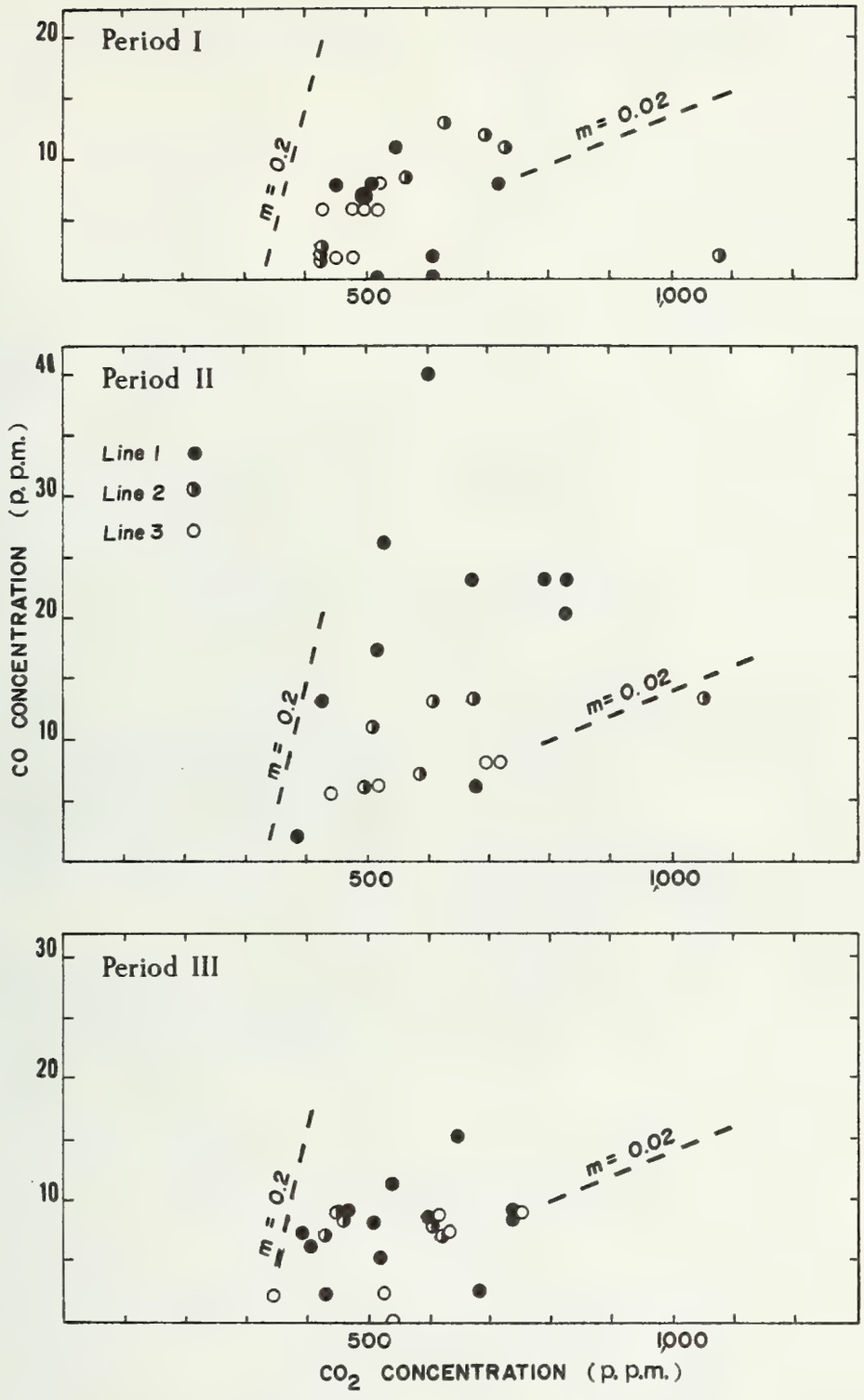


Figure 14. — Concentration of CO vs. CO_2, by period, for smoke collected in sample net from broadcast fire, Pack Forest, June 25, 1968. The slopes of the CO-CO_2 ratios are represented by m.

The stage II plume underwent rapid and apparently nonuniform dilution from the fire to the first line of samplers in the sample net. From line 2 through the remainder of the sample net, CO, CO_2, and probably the other plume components as well underwent uniform and less rapid dilution. Five points in figure 14 which represent samplers on line 1 lie on a line almost identical with the slope of the CO:CO_2 ratio from the 500° flame gases. The slope of the regression of all points along line 1 is much less — 0.025. The slope of the regressions for all points on lines 2 and 3 are 0.009 and 0.008, respectively — identical for practical purposes. The CO-axis intercepts of the two regressions are 3.85 and 2.01 for lines 2 and 3, respectively. This downward shift and constant slope of the regression would be expected for two gases diluting equally.

Samples PB-1, PB-3, and G-11 were taken as close to the fire as a man could walk without a fire suit.

Carbon monoxide readings taken directly in the smoke cloud at ground level with Monoxor chemical detector tubes were 40 p.p.m. early in period II. Thirty minutes later the readings were down to 20 p.p.m.

4.1.6.3. Hydrocarbon gases. — Infrared spectrophotometer analysis of gas samples from the fire area and from the air collected in the plume at 1,370 meters is shown in table 11. Description of the sample location is given above. Samples G-4 and G-2 were taken with the airplane and show only background levels of methane. Threshold limit values[12] of pollutants established for 1968 (Anonymous 1968) are listed as follows:

Pollutant	Maximum 8-hour concentration (P.p.m.)
CO	50
CO_2	5,000
MeOH	200
EtOH	1,000
Acetone	1,000
Benzene	25
Toluene	200
Xylene	100

Values of CO and CO_2 in the fire gas samples with the exception of samples taken in the fire were much lower than the limits.

Detailed analyses of gas samples by a combined gas chromatograph-mass spectrometer technique are shown in table 12. In general, the gas concentrations of all of the components are low.

The most significant components appear to be the low molecular weight hydrocarbons and alcohols including ethylene, ethane, propene, propane, methanol, and ethanol. Acetone and the aromatic compounds benzene and toluene also appear in most of the samples. Several unsaturated com-

[12] Threshold limit values are airborne concentrations of toxic materials to which workmen can be exposed 8 hours a day, 40 hours a week, without adverse effects.

Table 11.—*Infrared spectrophotometer analyses of smoke samples, broadcast fire at Pack Forest, June 25, 1968*

Component	PB-1[1]	PB-3[2]	G-11[3]	G-4[4]	G-2[4]
	Parts per million				
Carbon dioxide	490	820	580	330	320
Carbon monoxide	24	58	40	0	0
Methane	4	10	5	2	2
Ethylene	1	1	1	0	0

[1] PB-1, period II (see fig. 4 for location).
[2] PB-3, period II (see fig. 4 for location).
[3] G-11, period II (see fig. 4 for location).
[4] G-2, G-4 collected from smoke plume with airplane.

Table 12.—*Combined gas chromatograph-mass spectrometer analysis of smoke samples from broadcast burn, Pack Forest, June 25, 1968*

Component	Activated charcoal	Sample location						
		A-3[1]	I-1[2]	E-1[3]	PB-1[4]	G-11[4]	G-4[5]	G-2[5]
	Parts per million							
Ethylene	0.03	0.07	0.05	0.01	0.99	1.05	0.04	0.09
Ethane	.01	.02	.02	0	.50	1.25	.02	.05
Carbonyl sulfide	0	1.00	.50	.50	0	0	0	0
Propene	.13	.02	.01	0	.34	.70	.60	.01
Propane	.09	.01	.01	0	.21	.60	.01	.02
Methanol	0	3.07	1.92	1.60	1.03	2.86	.45	.34
Freon 12	.01	0	.90	0	0	0	0	0
Acetaldehyde	0	.04	.02	.03	0	0	0	0
Isobutane	.01	0	.21	0	0	0	0	0
Butene-1	.16	.05	0	.08	0	0	0	0
Ethanol	0	.18	.26	.06	.14	.10	.06	.15
Furan	.04	0	0	0	.12	.45	0	0
Acetone	0	.01	.05	.01	.24	.37	.02	.23
Dichloromethane	.01	.65	.48	.11	0	0	0	0
Dichlorethylene	.01	0	0	0	0	0	0	0
N-pentane	.01	0	.04	.01	0	0	0	0
Pentene-2	0	.02	.02	0	0	0	0	0
Methylfuran-2	0	0	0	0	.03	.17	0	0
Ethyl acetate	0	0	0	0	.39	.80	.03	.12
Benzene	.07	.04	.03	.03	.09	1.79	0	.01
2,4-dimethyl 2-pentene	0	.02	.02	0	0	0	0	0
N-heptane	0	0	0	0	.01	.72	.01	.01
1,1,2 trichloroethane	0	3.42	.44	.21	0	0	0	0
Toluene	.01	.07	.40	.03	.11	.09	.04	.02
Xylene	0	.04	.07	0	0	0	0	0

[1]Sample A-3 taken during period III.

[2]Sample I-1 taken during period II.

[3]Sample E-1 taken during period III.

[4]See figure 4 for location of PB-1 and G-11.

[5]See figure 1 for location of G-4 and G-2.

pounds in addition to ethylene and propene were identified, but the quantities found were relatively low.

The activated charcoal results represent a much larger sample of air than the bag or tank samples. Because of this, many compounds were detected which could not be seen in the small samples. Only compounds with concentrations of 0.01 p.p.m. or greater have been included in table 12 because of the uncertainties in identification at lower levels and also the increased likelihood of seeing background contaminants instead of compounds from the burn.

A number of compounds were detected that are known or suspected to have been introduced accidentally. Freon 12, for example, was found in samples near the nephelometer which employs this gas in its operation. Carbonyl sulfide was found only in bags sealed with black rubber stoppers. 1,1,2 trichloroethane was found only in those plastic bag samples which were not analyzed soon after collection. In retrospect, a number of anomalies in the data might be ascribed to gradual permeation into and out of the plastic bags. Permeation problems should not occur in the stainless steel tanks or in the activated charcoal sample which was stored in a sealed glass container until analysis. In future studies of this kind, special precautions should be taken to avoid potential changes in the samples while in storage.

4.2. Pile Fire

4.2.1. CARBON MONOXIDE AND CARBON DIOXIDE

In contrast to the broadcast fires, the pattern of combustion and emission of CO and CO_2 was nearly constant in pile fire sampled on July 11. Flame temperatures were higher and combustion was more complete. The fire was hot enough to ignite adjacent stumps and duff. Smoke from these spot fires was drawn into the plume of the pile and interfered with plume gas measurements.

The results of the CO and CO_2 analysis of samples taken from the fire are plotted in figure 15. The CO:CO_2 ratio is relatively constant throughout the fire except where smoke from the spot fires obscured it. In addition to its relative constancy, the CO:CO_2 ratio for the pile fire was considerably lower than the average for the broadcast fire, as expected.

The ratios obtained from the pile are lower than from an 850° flame in the broadcast fire, lower than the average in the sample net for period I, and lower than that obtained from the laboratory burn. This suggests that laboratory analysis does not take place under any better conditions for complete combustion than those which can occur in the field. That piled slash burns hotter and cleaner than broadcast slash is no revelation. However, fuel arrangement in laboratory burning experiments might be adjusted to give results closely paralleling field conditions.

4.2.2. PHOTOGRAPHY

Motion picture film of the pile fires taken at azimuths 90° apart were used to study: (1) the three-dimensional trajectory of four balloons; (2) the two-dimensional velocities of flames and smoke; (3) the diameter of the flames at different altitudes; (4) the development of eddies and fire blobs.

The results of the three-dimensional trajectory of four balloons and several two-dimensional velocities of flames and smoke are summarized in figure 16. Although flame speed of 18 m.sec.$^{-1}$ and smoke speed of 15 m.sec.$^{-1}$ were observed, the greatest frequency of flame speed appeared to be 3 m.sec.$^{-1}$ and represented laminar flow. In contrast, the speeds between 11 and 18 m.sec.$^{-1}$ represented extremely turbulent motion with strong horizontal components and erratic changes.

The colored motion pictures were also used to determine relative flame temperatures. For future work three color steps should be calibrated. This would result in flame temperature and possibly air composition data. One series of determinations is shown in figure 17. Three distinct portions of a free flame are described:

1. The inner, dark-reddish (i.e., "cooler") portion, which corresponds to the darker inner portion of a candle flame. This region seems to receive large amounts of distilled fuel gases as well as solid and liquid particulates from the fuel bed below. Oxygen supply is insufficient, and the mixture is very "rich." If portions of this cooler stream accidentally escape directly into the air after flaming out, one can observe a substantial flow of smoke. This seems to be the more important source of gaseous, liquid, and solid air pollution.

2. The yellow portion of "intermediate" temperature has much better oxygen supply from

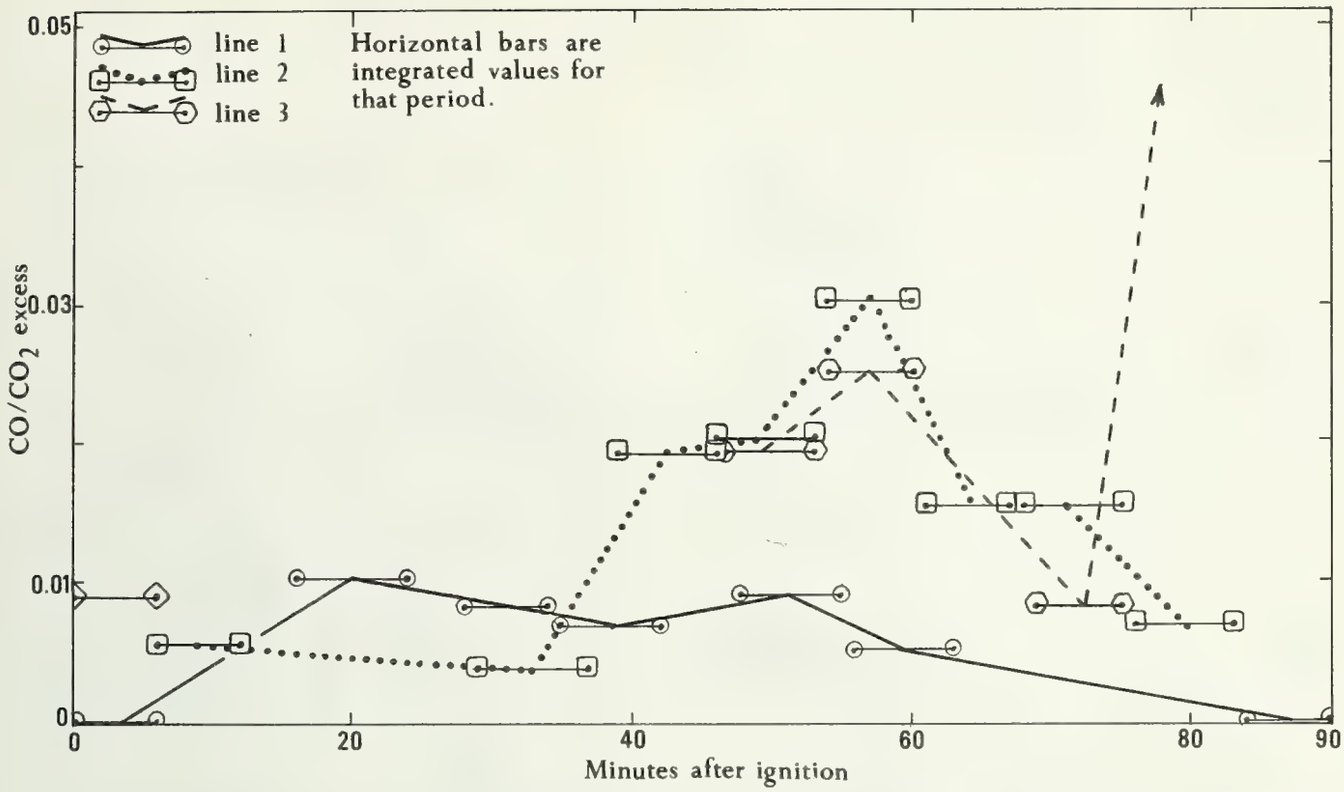
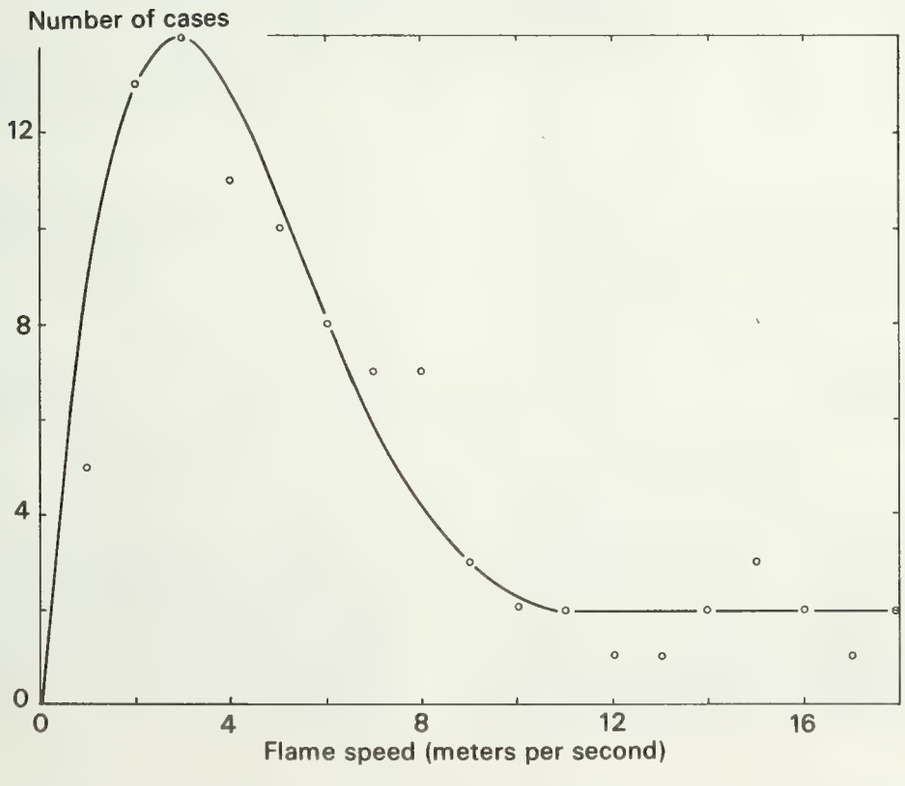


Figure 15. – Ratio of CO to CO_2 concentrations for smoke collected in water samples from pile fire, Pack Forest, July 11, 1968.

Figure 16. – Frequency of flame and smoke speeds observed from photography of pile fires.



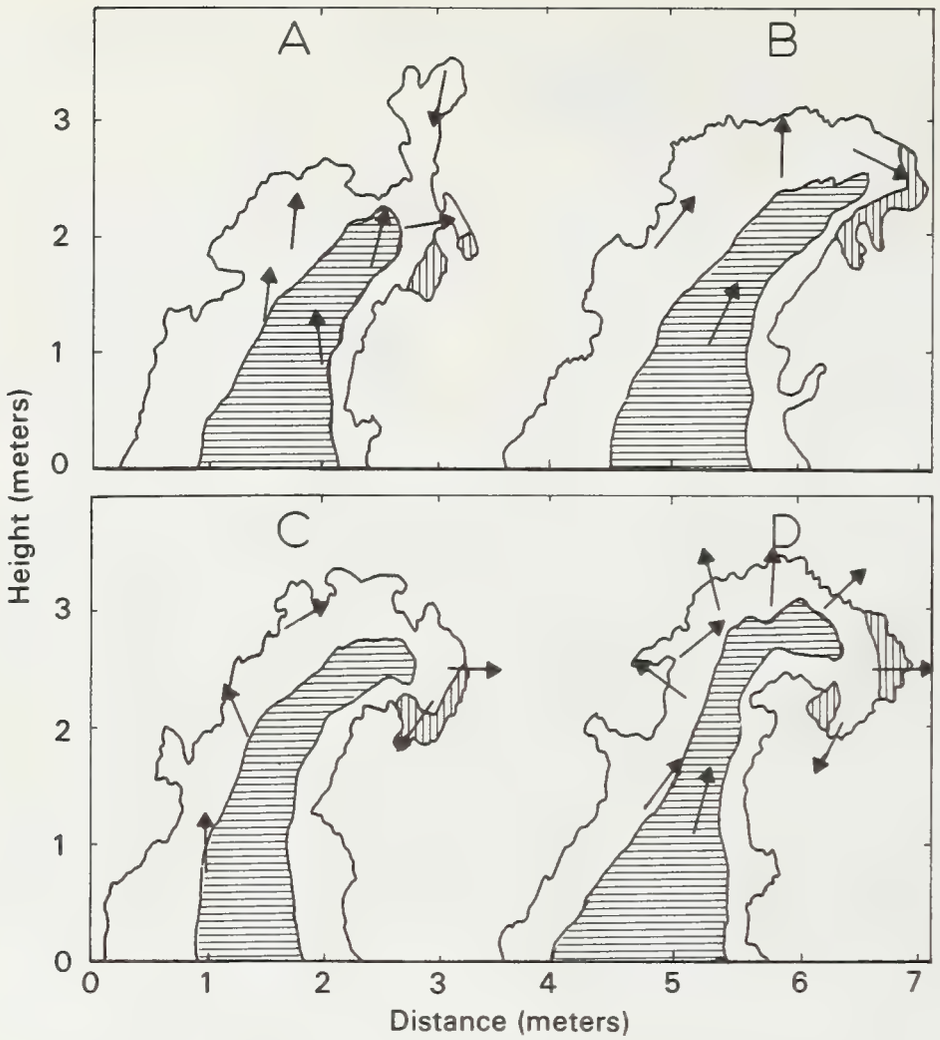


Figure 17. — Relative flame temperatures as determined from colored motion pictures of pile fires. Horizontal lines represent cooler portion, clear area represents intermediate temperatures, and vertical lines represent hottest temperatures.

sideways entrainment of fresh air. The mixture is less "rich" and the high radiation emission is due to large amounts of glowing particulates which are partially consumed in this part of the flame.

3. Once in a while small peripheral sections of bluish-white incandescence are seen. These hottest portions may very well reach a stoichiometric mixture and therefore temperatures may well exceed 1,000° K. In a candle flame, this portion is seen as a very thin blue mantle wrapped around the yellow flame. In this mantle the melting point of platinum, 2,000° K., is exceeded, as observations show. No smoke (solid or liquid light scattering particulates) issues from these hot portions. These white blobs do not contribute to air pollution.

4.2.3. MODELING OPEN FIRES

The three pile fires studied in this project were roughly cubical beds of packed wood. The resulting flame was slightly smaller in diameter and somewhat larger in height than the fuel bed. In these relative portions, they are quite different from a conflagration such as Hamburg (Germany) fire, resulting from bombing missions during World War II, where fire diameter far exceeded flame height which again far exceeded height of fuel bed; i.e., the average building. Former tests, conducted by G. Fahnestock in 1954 in Priest River, Idaho, and using flat fuel bed where no air could enter the fuel bed from below or from the sides, showed quite different behavior. In this case, the central

vertical flame diameter was about one-fifth of fuel-bed diameter.

These fires will be discussed with respect to four simple models: a chemical model, a rising airspeed model, a geometric model, and a pressure gradient model.

A simple chemical model of a flame may be the burning of 1 mole of $(CH_2O)n$ in 1 mole of O_2 into aliquot numbers of CO_2 and H_2O. Since measured CO_2 rarely exceeds 10 percent of the flame gas volume, a similar amount of combustion-created H_2O may be present. Burnable wood in general contains but a few percent of free water. The main mass of gas moving through a fire is therefore nitrogen. The total molar mass increase will barely exceed 10 percent. Since the volumes involved are strongly controlled by temperature and temperatures are not too well known, changes in masses moved as well as changes of average molecular weight may be neglected.

In a simple geometrical model, the flaming portion of a compact fire may be likened to a vertical cylinder of flame height (z_0) and radius (r_0). Into its periphery, an air volume of $\rho_0 \cdot u_0 \cdot 2\pi r_0 \cdot z_0$ ($m.^3 sec.^{-1}$), density = ρ, will be moved, and a nearly equal volume $\rho_1 \cdot w_1 \cdot r_0^2 \pi$ will leave at the top level of the flames (see chemical model). The coordinates used are as follows: x is the direction from an observer into the fire; v is the horizontal component perdendicular to x; z is the mean height; u, v, and w are vector flows in the x, y, and z directions. "Gradient" wind is the wind outside of the fire. Subscript 0 means near the fire border.

The speed of wind into the fire or fire storm may be obtained by equating the above products.

$$U_0 = \frac{\rho 1 \; w \, r_0}{\rho_0 \; 2 z_0} \qquad (1)$$

With environmental temperatures of 300° K. and flame temperatures of 900° K., $\rho_1/\rho_0 \approxeq 1/3$ or

$$U_0 \approxeq \frac{w \, r_0}{6 z_0} \qquad (2)$$

If observed values from the pile fires of r_0 = 6 meters, z_0 = 10 meters, and w = 8 $m.sec.^{-1}$ are used, the resulting value of U_0 should be about 0.8 $m.sec.^{-1}$. Such windspeeds could be observed only under calm conditions by very careful checking of flame motion.

If values of w = 20 $m.sec.^{-1}$, r_0 = 1,200 meters and z_0 = 100 meters for the Hamburg conflagration are assumed, the resulting horizontal windspeed should be approximately 40 $m.sec.^{-1}$. Values of 20 $m.sec.^{-1}$ have been reported near some ground conflagrations. The strongest winds will occur above the surface and will exceed 20 $m.sec.^{-1}$

A simple model for obtaining the rising speed of flame air, w_1, could depict the flame as either a rising balloon of hot air or a vertical cylinder of radius (r_0). At equilibrium, the forces of gravity (g) and drag are equal. For a sphere

$$\triangle \rho g \frac{4\pi {r_0}^3}{3} = \rho_0 \, \pi {r_0}^2 w^2 \qquad (3)$$

$$\text{where } \triangle \rho = \rho_0 - \rho_1 . \qquad (4)$$

If the values for the pile fires $\triangle \rho / \rho_0 = 2/3$ are used, then

$$w = \left(\frac{\triangle \rho \, g}{\rho_0} \frac{(4 r_0)}{3} \right)^{1/2} \approxeq (10 \, r_0)^{1/2} \qquad (5)$$

It is doubtful whether the whole flaming area of Hamburg of r_0 = 1,200 m. created one continuous ball, or indeed, if the above equation can be applied to such large areas. Solving the above equation with the pile fire data $w \approxeq 7$ $m.sec.^{-1}$ was anticipated and observed (see section 4.2.2). Finally, a w = 4 $m.sec.^{-1}$ could be expected from the California Project Flambeau fires of r_0 = 160 meters.[13] By use of pulsed radar, w = 20 $m.sec.^{-1}$ was observed.

The vertical motion, w, is not the cause of the fire wind. It is the result of the horizontal pressure gradient ∇p created by the visible flame air and smoke air. Maximum U_0 and ∇p will be created under calm conditions because all of the hot air is above the fire. Increasing gradient winds will cause the hot air column to tilt thereby reducing U_0.

According to Buettner (1967), the general equation for motions can be written as

$$\frac{d(\rho V)}{dt} = -\nabla p \qquad (6)$$

if we neglect friction and Coriolis forces. Simplifying further by having only component u in a

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[13] Personal communication with Thomas Y. Palmer, Pacific Southwest Forest and Range Experiment Station, Riverside, California.

vertical flame wall, we have

$$\partial\mu\,(\rho u) / (\partial x) = -(\partial p) / (\partial x) \qquad (7)$$

or integrated

$$\rho u^2 = -\triangle p \qquad (8)$$

if u_g is zero.

The pressure difference ($\triangle p$) between free air and fire, near the surface, is $-\triangle p = z_0 . g \triangle \rho$ where z_0 is flame height. (9)

Using the same data as before, we find $\triangle p = 0.67$ millibars for a flame height of 10 meters. Combining equations 8 and 9, we have the fire storm or into-fire wind as

$$u = (z_0\, g\, \triangle\rho/\rho)^{1/2} \qquad (10)$$

or with $g = 10$ m.sec.$^{-2}$ and $\triangle\rho/\rho = 2/3$

$$u = 2.6\, z_0{}^{1/2}$$

In the Hamburg fire, values of z_0 were in excess of 100 meters resulting in $u_0 = 26$ m.sec. or more.

A more refined theory should take into account:

a. the conical form of smaller fire flames and the consequent $\triangledown p$ pattern

b. the combination of equations of motions and of conservation of mass

c. the effect of the shrinking diameter through which air moves into the fire if this is essentially a cylinder or a cone

d. the effect of the step-function of u at the fire border where suddenly ρ drops drastically.

4.3. Laboratory Fire

Results of the microanalysis and the average concentrations of major pollutants during burning of the slash samples are given in table 13. These data are especially interesting because the absolute quantities of emissions can be monitored more or less completely, and a carbon balance can be written for each fire. Carbon balances recorded on grassy material burned in the same fashion typically fall between 95 and 99 percent. Since this was the first experiment with logging slash materials, the rather large variations in carbon balance for these fires are largely unexplained.

Trends of temperature from five laboratory fires are shown in figure 18. The temperature curves show different burning characteristics for similar quantities of fuel from the same species. The differences are unexplained and could be due to differences of fuel packing and ignition.

4.3.1. PARTICULATE MATTER

Particulate matter production from the five samples are reported in table 13 as grams of smoke per kilogram of fuel. All samples yielded about the same amount of smoke.

4.3.2. CARBON MONOXIDE AND CARBON DIOXIDE

Cumulative CO_2 production curves are shown in figure 19. For similar species, CO_2 production between samples occurred during the equilibrium burning period. More CO_2 was produced by the western redcedar samples than by western hemlock or Douglas-fir.

Carbon monoxide production from the five samples appeared similar to CO_2 production (fig. 20A).

The ratio of CO to CO_2 from the laboratory fires was similar to the ratio during period I of the broadcast fire (4.1.6.2) and slightly greater than the ratios from the pile fire (4.2.1).

4.3.3. HYDROCARBONS

Production of total hydrocarbons is reported as "C" in table 13. Trends are shown in figure 20B. Hydrocarbon production appeared to be greatest from western redcedar with Douglas-fir second and western hemlock third. Total hydrocarbon production from western redcedar was similar to that from dry native brush and fruit prunings as reported by Darley et al. (1966) and much lower than hydrocarbon production in rice and barley straw.

Individual hydrocarbons from the laboratory fires are shown in table 14. The concentration of individual hydrocarbons obtained from the laboratory samples were essentially the same as those obtained from the broadcast fire (4.1.6.3). Since the hydrocarbon concentrations were similar, the absolute values in grams per kilogram of fuel from the laboratory can be said to estimate hydrocarbon production from the field.

Table 13.—*Laboratory analysis of combustion products from Douglas-fir, western hemlock, and western redcedar slash*[1]

Sample	Sample weight	Microanalysis[2]		Moisture content	Smoke	CO	CO_2	C (hydrocarbons)	$CO:CO_2$	Residue	Carbon balance
		Carbon	Hydrogen								
	Kilogram	*Percent sample weight*		*Percent ovendry weight*	*Grams*[3]					*Grams per kilogram*	*Percent*
Hemlock 1	11.4	63.39	1.82	8.4	2.0	30	1,030	1.2	0.02939	1.9	79
Hemlock 2	12.1	67.65	1.73	8.4	2.0	46	1,213	1.2	.03628	1.6	93
(wood)	–	47.88	6.42	–	–	–	–	–	–	–	–
Douglas-fir 1	8.2	59.67	1.95	7.2	2.3	32	1,143	1.6	.02828	1.5	89
(wood)	–	46.84	6.46	–	–	–	–	–	–	–	–
Western redcedar 1	11.0	62.77	1.90	7.2	1.7	56	1,554	2.2	.03636	1.0	109
Western redcedar 2	11.0	56.98	1.62	7.2	2.2	59	1,395	2.2	.04212	2.9	110
(wood)	–	47.36	6.49	–	–	–	–	–	–	–	–

[1] Analysis by E. F. Darley.

[2] Analysis by Elek Micromanalytical Laboratories, P. O. Box 1156, Walteria Sta., Torrance, Calif. 90505.

[3] Per kilogram of fuel.

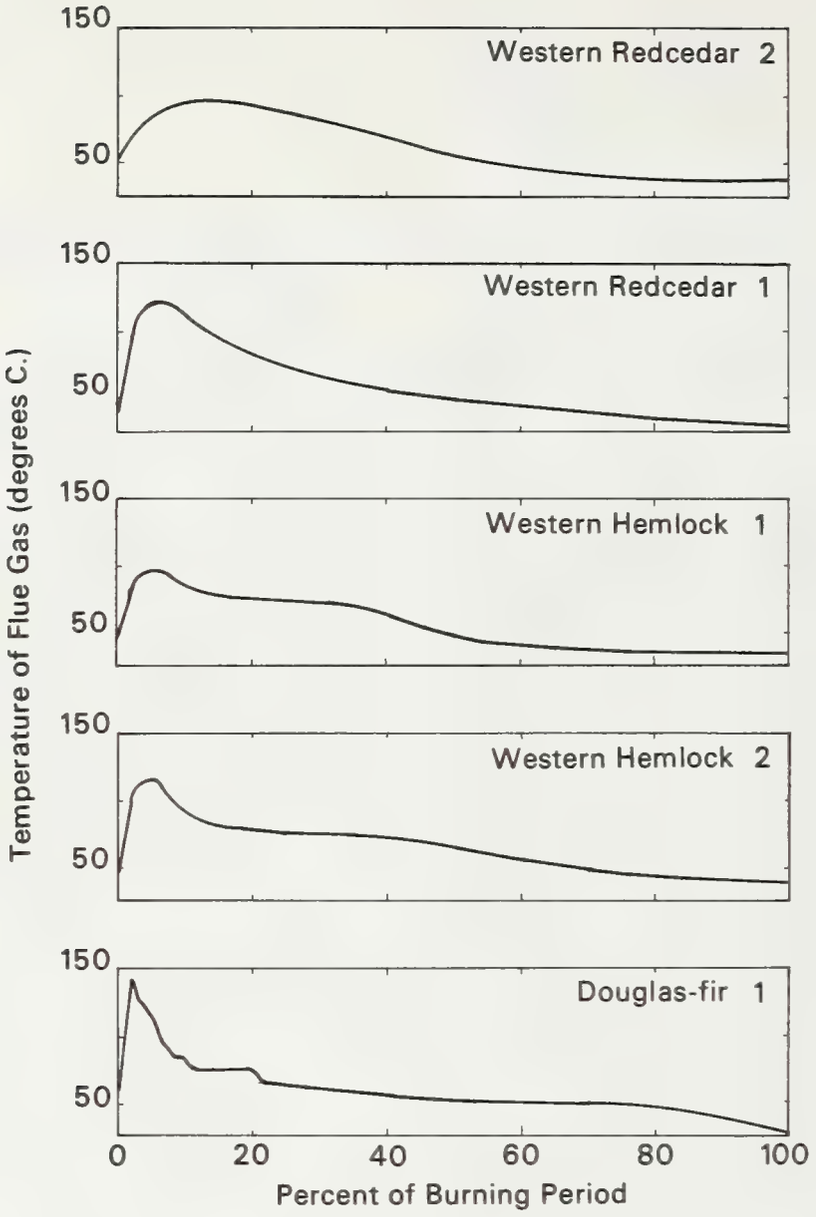

Figure 18. — Gaseous temperature in relation to percent of burning time of fire laboratory samples.

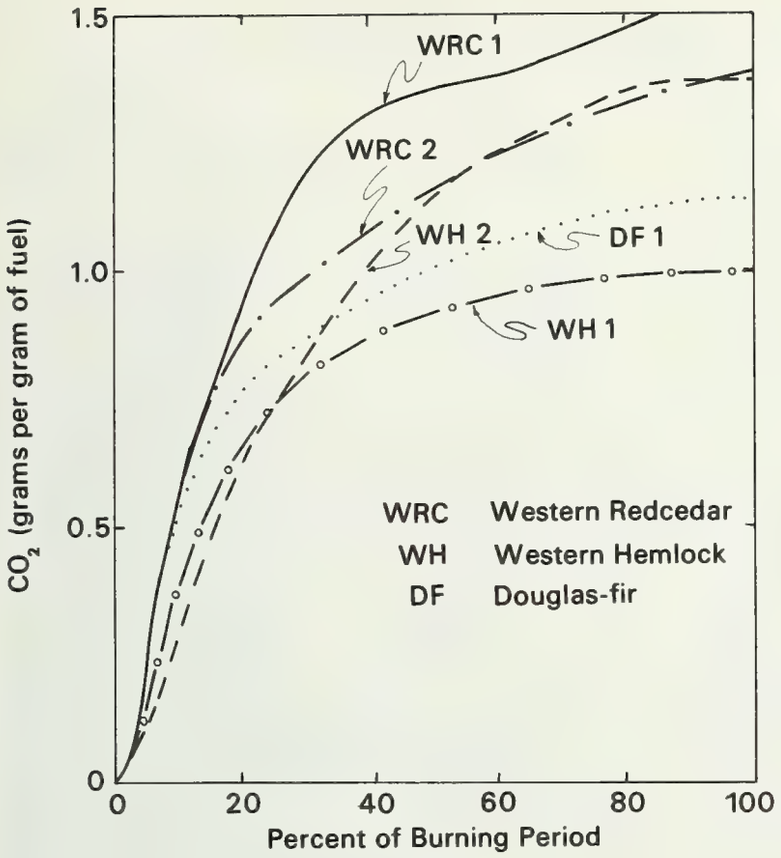

Figure 19. — Cumulative CO_2 production from five laboratory samples.

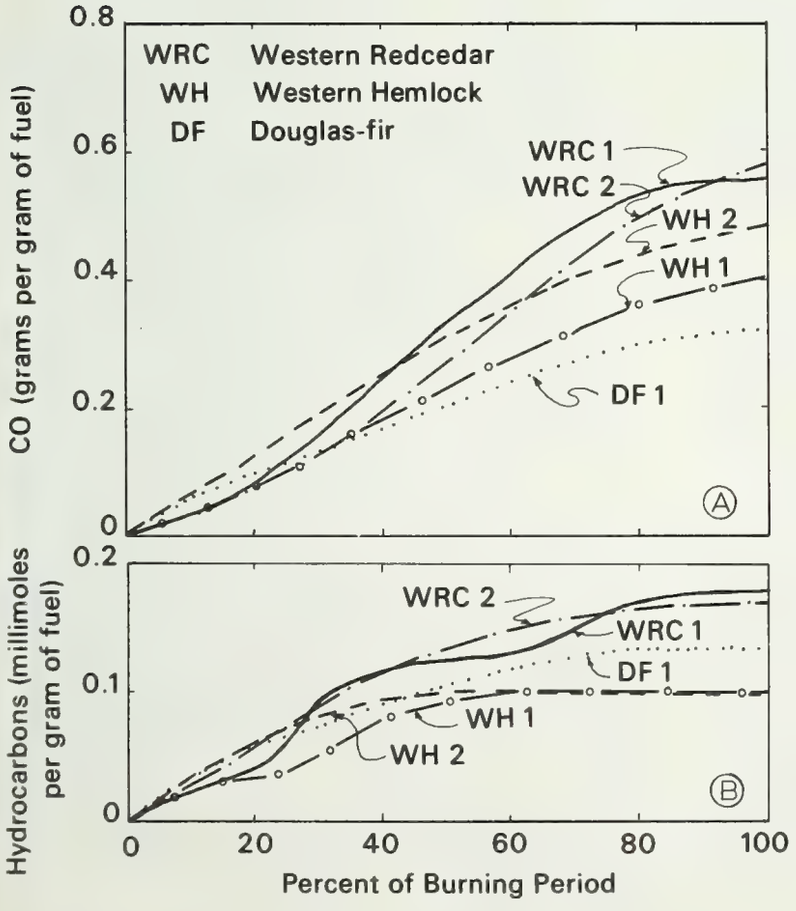

Figure 20. — *A*, Cumulative CO production from five laboratory samples; *B*, hydrocarbon production from five laboratory samples.

Table 14.—*Gas chromatographic analyses of smoke samples from five laboratory fires, by number of minutes after fire start*

Gas	Western hemlock sample No. 1			Western hemlock sample No. 2			Douglas-fir			Western redcedar sample No. 1			Western redcedar sample No. 2		
	2 min.	7 min.	17 min.	1.5 min.	7 min.	18 min.	1 min.	5 min.	16 min.	2 min.	5 min.	16 min.	2.5 min.	8 min.	19 min.
	Parts per million														
Methane	3.2	—	13.2	3.2	4.8	8.3	2.0	0.7	9.3	3.5	5.2	11.2	10.0	4.3	7.8
Ethene	1.0	—	1.4	1.2	.6	.6	.6	.9	1.0	1.3	.8	.9	5.2	.5	.6
Ethane	.1	—	.6	.1	.2	.3	.6	.3	.5	(1)	.3	.4	.7	.2	.3
Acetylene	.6	—	.1	.7	.3	.2	.3	.3	.2	.7	.3	.3	2.5	.1	—
Propane	(1)	—	.4	(1)	2.7	(1)	(1)	.1	.2	(1)	.1	.3	.2	(1)	(1)
Propene	.2	—	.5	.3	.1	.1	.1	.3	.5	.3	.2	.3	1.1	.2	.2
Isobutane	—	—	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
N-butane	(1)	—	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Acetylene	.7	0.1	.5	.8	.2	.1	.5	.3	.2	.8	.3	.3	2.9	.3	.2
1-butene	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	.2	(1)	(1)
Isobutene	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	.1	(1)	(1)
Trans-2-butene	(1)	(1)	(1)	(1)	—	—	—	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Isopentane	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Cis-2-butene	(1)	(1)	(1)	(1)	—	—	—	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
N-pentane	—	—	—	—	—	(1)	—	—	—	—	—	—	—	—	—
3-methyl butene-1	(1)	(1)	(1)	(1)	(1)	—	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
1,3-butadiene	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	.3	(1)	(1)
1-pentene	(1)	(1)	—	—	—	—	(1)	(1)	—	(1)	(1)	(1)	(1)	—	—
2-methyl butene-1	—	—	—	—	—	—	—	—	(1)	—	—	—	(1)	—	—
Trans-2-pentene	—	—	(1)	—	—	—	—	—	—	—	—	—	(1)	—	—
2-methyl butene-2	—	—	—	—	—	—	—	—	(1)	—	—	—	—	—	—

[1] Less than 0.1 p.p.m. Methane, ethane, ethene, and acetylene were analyzed by use of a 5-foot Poropak N column at 60° C. All others were analyzed by use of a 36-foot, 10-percent DMS column at 0° C.

5. DISCUSSION AND CONCLUSIONS

The relationship between the current practice of slash burning and air pollution was investigated with broadcast and pile fires in the field and laboratory fires. The hypothesis tested was that incomplete combustion and consequently greater emissions result from low-temperature fires. In our experiments, the broadcast fires represent low-temperature fires whereas the piles and laboratory fires represent higher temperature fires. These experimental fires were investigated with respect to burning characteristics and gaseous, hydrocarbon, and particulate emissions. The results of each fire are summarized individually.

The broadcast burn was center-fired by power boosters. In 15 minutes, a strong convection column had developed which penetrated a lower inversion at 640 meters and sheared at 1,370 meters. The convection column began to bend over with the prevailing wind 25 minutes after ignition and by 90 minutes after, only disorganized small sources of smoke remained. From photography and meteorological observations, three fire stages were described, the buildup, diedown, and isolated hot spots.

Ground particulate samples indicated an increase of nearly 10 times the background level immediately downwind from the fire during the second stage. The particulates in the smoke plume in the fire vicinity reduced visibility to 0.5 kilometer, but at a distance of 19 kilometers from the fire the visibility had increased to the level found over Seattle.

Similarly, high CO and CO_2 concentrations found at the fire site decreased rapidly to ambient conditions in horizontal and vertical directions. CO:CO_2 ratios increased from 0.034 during the buildup stage to 0.051 during the isolated hot spot stage. CO:CO_2 ratios from 850° C. flames were similar to those from the laboratory fires.

Hydrocarbon analyses of gas samples revealed low concentrations of 25 components, the most significant of which appear to be the low molecular-weight hydrocarbons and alcohols including ethylene, ethane, propene, propane, methanol, and ethanol. Several unsaturated compounds were found, but the quantities were relatively low.

In contrast to the broadcast fire, the pattern of combustion and emission was more uniform in the pile fires. The CO:CO_2 ratios were nearly constant throughout the pile fire and were lower than from the 850° C. flames in the broadcast and laboratory fires.

Analysis of laboratory fires of Douglas-fir, western hemlock, and western redcedar revealed three fire stages: the buildup, diedown, and equilibrium stage. The length of each stage appeared to be related to the total charge, fuel packing, density, and composition. The burning characteristics of the Douglas-fir laboratory fire were similar to the broadcast fire. Analyses of the gases revealed CO and CO_2 emissions similar in magnitude to those from burning other agricultural residue. The total hydrocarbon level appeared to be lower. The CO:CO_2 ratios from the laboratory fires were similar to those from the broadcast fire indicating a similar degree of combustion.

The results of these tests suggest that broadcast fires can be modeled in the laboratory with respect to burning characteristics, gaseous and particulate emissions from different fuel density, packing, and quality and method of ignition. Furthermore, these tests indicate that establishing a high energy fire with a strong convection column under conditions favorable for rapid atmospheric dispersion can minimize the air pollution aspects of slash burning. These conditions may be achieved by a balance of local fire behavior management with meteorological management of smoke.

Fire behavior management includes techniques of fuel modification, electrical ignition and fuel booster systems, and firing sequences, all aimed at obtaining quick, positive ignition and rapid fire development with complete combustion of unwanted fuel.

Meteorological management may include burning under an unstable atmospheric profile, when windspeeds are sufficiently high to advect smoke, and when wind directions are away from populated areas.

Slash burning may have to be done in all seasons: fall, winter, spring, and summer. Yearlong burning may be necessary to obtain enough burning days when the air pollution threat can be minimized by some trade-off between local fire behavior management and meteorological management. In late winter or spring, large fuels may still

have high fuel moistures, and fires of short duration consuming only the smaller fuels – quick, hot fires – will result. In late summer or fall when heavy fuels are dry, residual glowing combustion, as typified by stage III of this study, may result. Total emissions output may be relatively high over long periods of unfavorable dispersal conditions (nighttime subsidence and inversions). Burning early in the day and establishing a high rate of energy release during this more stable period may overcome this type of air pollution threat. Decreasing energy release rates will be offset by increasing atmospheric instability later in the day. Chances of burnout of all available fuels, including the heavy fuels, will be increased.

In general, the concentrations of gases and hydrocarbons found in gas samples taken under field conditions were similar to those taken under laboratory conditions. Concentration of gases and hydrocarbons diluted rapidly to ambient or background values. Particulate emissions in the smoke plume were high but decreased in 20 kilometers to values found over the Seattle area.

In addition to the air pollution aspects, the following significant findings and developments resulted from this research project: The airborne version of the integrating nephelometer used in these studies was developed and flight tested; air samplers, capable of operating without power, were developed to collect air samples over a period of time; the vacuum oven technique proved to be the most reliable and practical method of determining fuel moisture; and the peak frequency of flame speeds was found to be 3 $m.sec.^{-1}$.

6. SUMMARY

This is a report on an investigation, conducted under a grant from the U.S. Forest Service to the University of Washington, of the current practices of slash burning in relation to air pollution.

The hypothesis was that incomplete combustion and greater emissions result from low-temperature fires. Low-temperature fires were associated with broadcast burns. Piled slash was expected to burn more completely and at higher temperatures; hence, would produce less pollution. The results of field tests were compared with laboratory burns with respect to burning characteristics and gaseous and particulate emissions.

The more salient conclusions are:

1. Ground level particulates increased to nearly 10 times the background immediately downwind from the broadcast burn. The particulates in the smoke plume in the vicinity of the fire reduced visibility to 0.5 kilometer, but at a distance of 19 kilometers from the fire, the visibility had increased to the level found over Seattle.

2. Similarly, high CO and CO_2 concentrations found at the fire site decreased rapidly to ambient conditions in horizontal and vertical directions.

3. Hydrocarbon analyses of gas samples revealed low concentrations of 25 components, the most significant of which appeared to be the low molecular weight hydrocarbons and alcohols including ethylene, ethane, propene, propane, methanol, and ethanol. Several unsaturated components were found but the quantities were relatively low.

4. Results suggest that broadcast fires can be modeled in the laboratory with respect to burning characteristics, gaseous and particulate emission from different fuel density, packing, composition, and method of ignition.

5. Air pollution aspects of slash burning can be minimized by a high energy release rate fire with a strong convection column under conditions favorable for rapid atmospheric dispersion. The fire should be of short duration to consume the smaller fuels only.

7. FUTURE RESEARCH

Areas of additional research, suggested as a result of this project, are:

1. Ignition systems for different fuels, weather, and topography to minimize air pollution.
2. Fuel booster systems to achieve rapid high temperature and rate of energy release build-up.
3. Practical methods of energy budget analyses to aid in decisionmaking of prescribed burning time and technique.
4. Climatological study of potential temperature surfaces and drift patterns to aid in scheduling burning.
5. Economic analyses of alternative burning techniques.

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9. APPENDIX

9.1. Carbon Monoxide and Carbon Dioxide Data

9.1.1. BROADCAST FIRE

Table 15.—*Analysis of CO and CO_2 collected in water-displacement air samplers during broadcast burn, Pack Forest, June 25, 1968*

Location	Period I		Period II		Period III	
	CO	CO_2	CO	CO_2	CO	CO_2
	Parts per million					
A 1	8	450	—	450	—	—
A 2	—	—	—	—	—	—
A 3	6	427	8	697	2	337
B 1	7	495	17	517	8	517
B 2	2	427	7	585	7	630
B 3	7	495	6	526	7	630
C 1	—	—	—	—	11	540
D 1	11	549	26	531	—	—
D 2	2	1,080	6	495	8	607
D 3	2	472	6	436	11	630
E 1	12	697	13	607	8	607
F 1	—	517	2	382	8	463
F 2	8	562	11	508	7	427
F 3	2	450	—	—	6	855
G 1	6	487	20	832	2	684
H 1	—	—	—	495	6	405
H 2	6	495	—	470	8	463
H 3	—	—	—	—	—	—
I 1	6	472	40	607	2	427
J 1	8	720	23	796	—	—
J 2	11	729	13	679	—	—
J 3	—	495	—	967	—	540
K 1	—	—	23	832	—	—
L 1	2	607	23	675	8	742
L 2	2	427	13	1,057	8	463
L 3	8	517	8	720	2	526
M 1	8	508	6	675	7	391
N 1	—	607	13	430	5	517
N 2	—	405	—	—	—	—
N 3	6	517	6	495	—	—

9.1.2. PILE FIRE

Table 16.—*CO and CO_2 concentrations in samples taken during pile fire, Pack Forest, July 11, 1968*

Line 1[1]			Line 2[1]			Line 3[1]		
Time sample started[2]	CO	CO_2	Time sample started[2]	CO	CO_2	Time sample started[2]	CO	CO_2
	Parts per million			*Parts per million*			*Parts per million*	
1237	0	449	1240	—	([3])	1239	6	972
1247	—	([3])	1250	2	671	1248	—	([3])
1255	1	416	1258	—	([3])	1325	5	578
1307	—	([3])	1308	1	578	1333	25	1,318
1314	1	462	1318	5	578	1340	—	([3])
1321	10	671	1325	2	419	1348	1	439
1327	25	430	1333	5	487	1355	45	1,041
1335	25	763	1340	2	449			
1343	2	763	1347	2	449			
1353	0	462	1402	1	462			

[1] Location of sample lines shown in figure 5.
[2] Average sample period was 7 minutes.
[3] Sample container destroyed by heat from fire.

9.2. Conversion Factors

1 centimeter (cm.)	=	0.0394 in.
1 inch (in.)	=	2.54 cm.
1 meter (m.)	=	3.28 ft.
1 foot (ft.)	=	0.305 m.
1 kilometer (km.)	=	0.621 stat. mi.
1 stat. mi.	=	1.609 km.
1 hectare (ha.)	=	2.471 acre
1 hectare (ha.)	=	$10^4 m.^2$
1 liter (l.)	=	0.264 gal.
1 gallon (gal.)	=	3.785 l.
1 meter per second ($m.sec.^{-1}$)	=	2.236 m.p.h.
1 mile per hour (m.p.h.)	=	0.447 $m.sec.^{-1}$
1 gram (g.)	=	0.00220 lb.
1 pound (lb.)	=	453.6 g.
1 metric ton (5)	=	1.102 short ton
1 short ton	=	907.2 kg.
1 cal.	=	0.00397 B.t.u.
1 B.t.u.	=	252 cal.

Fritschen, Leo; Bovee, Harley; Buettner, Konrad; and others.

1970. Slash fire atmospheric pollution. USDA Forest Serv. Res. Pap. PNW-97, 42 pp., illus. Pacific Northwest Forest & Range Experiment Station, Portland, Oregon.

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